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VIRTUAL MANUFACTURING OF COMPOSITE STRUCTURES FOR GROUND PLATFORMS

A DARPA Instant Foundry Adaptive Through Bits (iFAB) Program

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Final Report

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14. ABSTRACT
This effort focused specifically on the Liquid Composite Molding (LCM) class of processes as they are the ideal processes for medium to large scale components for ground platforms. UD-CCM has long history of fabricating composite structures for ground vehicles using these processes and the Figure below shows some examples of components fabricated over the years. The goal in this effort is to link composites design with process modeling, enabling the designer to evaluate manufacturability of the components in question. Historically, this has been a sequential process with component design and analysis followed by manufacturability assessment, usually through model fabrication runs or trial and error. The goal is to move to a concurrent approach, to significantly reduce the time from component design to functional prototype stage.

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Liquid Composite Molding (LCM), fabrication, manufacturability assessment

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Summary

The University of Delaware Center for Composite Materials (UD-CCM) has developed the Composites Manufacturability Evaluation System (CMES), a software tool that provides manufacturability assessments for composite components for the Liquid Composite Molding class of processes. The core of CMES is a physics-based process modeling tool called LIMS (Liquid Injection Molding Software) that predicts resin flow and filling of complex 3-D geometries with a selected reinforcement or fabric. Process variability is quantified using a probabilistic approach to look at variations in material properties, process parameters and process disturbances. Manufacturability assessments are done at three (3) levels of abstraction ranging from feasibility assessments (Level 0), process variant assessment (Level 1) and probabilistic assessment of the selected Level 1 process. CMES performs these analyses within the scope of a specific foundry configuration, hence the capabilities of the composites foundry that is being considered for component fabrication need to be documented. Modifications to the component design can be performed based on these recommendations and resubmitted for CMES analyses.

For each level of abstraction, CMES provides assessments and design/process recommendations to the user. Level 0 evaluates process feasibility and only requires material data, component bounding box and foundry capability. Level 1 provides part cycle times, infusion schemes and a recommended process selection back to the user, in addition to manufacturability assessment. Level 2 provides a probabilistic evaluation of the recommended Level 1 process scheme with yield vs process scheme, cycle time variability and a summary of dominant parameters that affect variability. CMES validations have been performed for a variety of components ranging from simple geometries (flat laminates) to complex doubly curved geometries (composite vehicle hood with stiffeners).

1 INTRODUCTION

This effort focused specifically on the Liquid Composite Molding (LCM) class of processes as they are the ideal processes for medium to large scale components for ground platforms. UD-CCM has long history of fabricating composite structures for ground vehicles using these processes and the Figure below shows some examples of components fabricated over the years. The goal in this effort is to link composites design with process modeling, enabling the designer to evaluate manufacturability of the components in question. Historically, this has been a sequential process with component design and analysis followed by manufacturability assessment, usually through model fabrication runs or trial and error. The goal is to move to a concurrent approach, to significantly reduce the time from component design to functional prototype stage.

Figure 1 Example Composite Structures fabricated using Liquid Composite Molding processes.

1.1 LIQUID COMPOSITE MOLDING (LCM)

Liquid molding is the process of choice for medium to large-scale composite structures, due to its ability to scale to very large sizes at low costs. Examples include wind blade fabrication, Navy ship topside structures, marine, civil infrastructure and aerospace industries. Ground platform structures are ideally suited for liquid molding processes and UD-CCM has demonstrated the ability to fabricate high quality composite structures for both tactical and combat vehicle platforms in prior programs.

The current practice to fabricate polymer composites is to place fibrous reinforcement (called a preform) into a mold to build it up a required thickness and inject a polymer resin into it. The mold is closed or sealed with a plastic bag and a liquid resin is infused to saturate the preform. Usually, thermosetting resin is used because of its lower viscosity. After injection, the resin is allowed to cure (cross-link). Once it is solidified, the part is de-molded. This technique allows manufacturing of complex shape parts in a single step.

The reinforcement usually consists of one or multiple layers of woven or stitched fabric made of glass, carbon or aramid fiber, though other architectures and materials (such as bio-fibers) are occasionally used. To manufacture a successful composite, the resin must saturate all

the empty spaces between the fibers and fiber tows. Any regions in the final part that are devoid of resin (referred to as micro or macro voids) will have a detrimental effect on the final and functional properties of the composite. Hence the fiber lay-up and architecture and the injection scheme are intimately interlinked with the final performance of such composites.

1.1.1 LCM Process Variations

Two widespread techniques in this process are Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM), but there are several other processes of interest, such as Membrane VARTM or RTM "Light" considered herein. There are other variants as well, such as the Compression Resin Transfer Molding (CRTM). Figure 2 schematically compares the relevant processes.

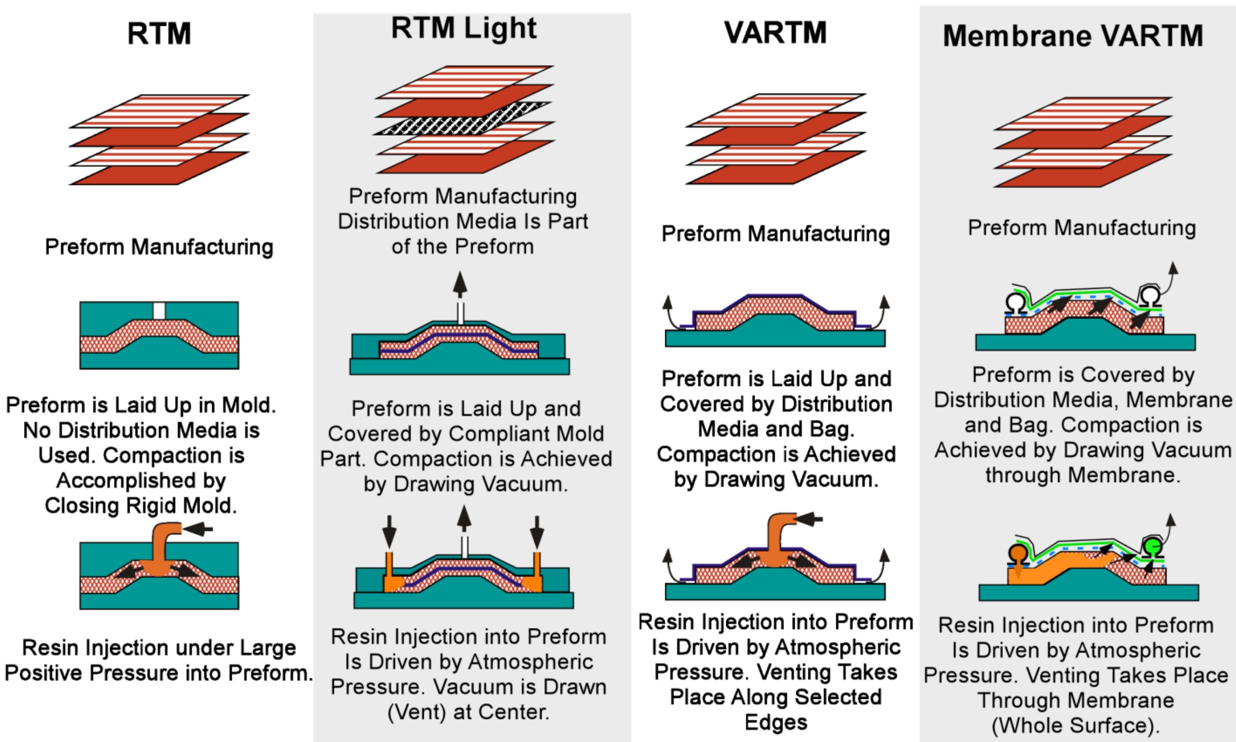


Figure 2 Comparison of Resin Infusion Strategy in Relevant LCM Process Variations.

In RTM, the mold is two sided and rigid. This yields complex parts with very good surface quality and excellent dimensional tolerance and also allows the maximal fiber volume fraction to be achieved. The infusion in this case is very susceptible to flow disturbances, but the rigid tool can obviously mount sensors and controllers to deal with the problem. On the other hand, the tooling and equipment cost limits this method to relatively small parts. The process rate is limited by the need to "push" the viscous resin through the highly compacted preform. Consequently, the injection process may take significant time, but that is true of all process variations considered here.

In VARTM (VIP), one side of the mold is replaced by a compliant vacuum bag and a vacuum is drawn, compacting the preform and "drawing" the resin in. As a result, the bag side surface is not class 'A' finish and the dimensional tolerances may also be compromised. On the

other hand, tooling cost is significantly reduced and large parts can be manufactured. The sensitivity to flow disturbances is lowered in this process as the edges may be sealed by the bag.

As the injection is driven by atmospheric pressure, it is usually necessary to help the resin flow by introducing a flow enhancement media which is a highly permeable layer that distributes the resin over the part surface. Even with this assistance, the filling of preform with resin may take many hours. This problem is usually addressed by sequential filling strategies with multiple inlets activated as the flow progresses. After the part cures, the vacuum bag, the flow enhancement media and the tubing, etc. need to be separated from the part and discarded which is time and labor intensive.

RTM Light is actually very similar to VARTM. It replaces the vacuum bag with a compliant mold and, usually, incorporates specialized distribution media into the preform where it remains a part of the product. Consequently, the surface quality is improved relative to VARTM. The thickness variation may remain an issue. The sensitivity to flow disturbances is reduced by making the outer edge the infusion line, and the resin tends to be temporarily bled through the central venting position to eliminate void created by slightly shifted flow patterns. As two sided mold is involved, part size is again limited, but the limits are more generous than with RTM.

Membrane VARTM process differs from standard VARTM in the application of the vacuum. The surface is covered by a semi-permeable membrane that allows the volatiles to escape but keeps the resin in. Vacuum is drawn through this membrane, providing essentially a “surface” vent over whole part, thus removing sensitivity to flow disturbances, at least for moderately thick parts. There is, however, a significant increase in cost and some limits to the part shape as the available membrane materials do not deform in shear, making doubly curved surfaces difficult to make.

All the infusion process variations described above are slow processes because of various limits on flow driving pressure and limited permeability of the reinforcement system. It needs to be kept in mind, however, that preforming itself is slow process and de-molding may be time consuming too particularly with VARTM and Membrane VARTM. If rapid processing and fast turnaround is required, all these issues have to be addressed, for example by net-shape 3D preforming and Compression RTM. This is beyond the current study.

2 METHODS, ASSUMPTIONS AND PROCEDURES

2.1 CMES Methodology for LCM

The CMES tool developed in this effort will provide process planning and design feedback capability for LCM processes in composite structures. For a given set of design inputs, the CMES will generate process plan(s) with manufacturability metrics (quality, cost, throughput etc) and provide feedback to the designer with recommendations to improve metrics. CMES is also executed within the constraints of the specified foundry (documented in a Foundry Specification file), while retaining the flexibility to change the specification, if alternate or additional foundries are available. Completion of the design-manufacturability analysis loop results in the generation of an optimal process plan that meets requirements, which then translates to work instructions in the Composite Foundry. At this stage the instruction generation is semi-automated through the use of standard electronic documentation templates. From a

design to component time compression perspective, work instruction generation is generally a small component of the overall time, so no significant investment is planned to automate this aspect. The overall scheme of CMES is shown in Figure 3 below.

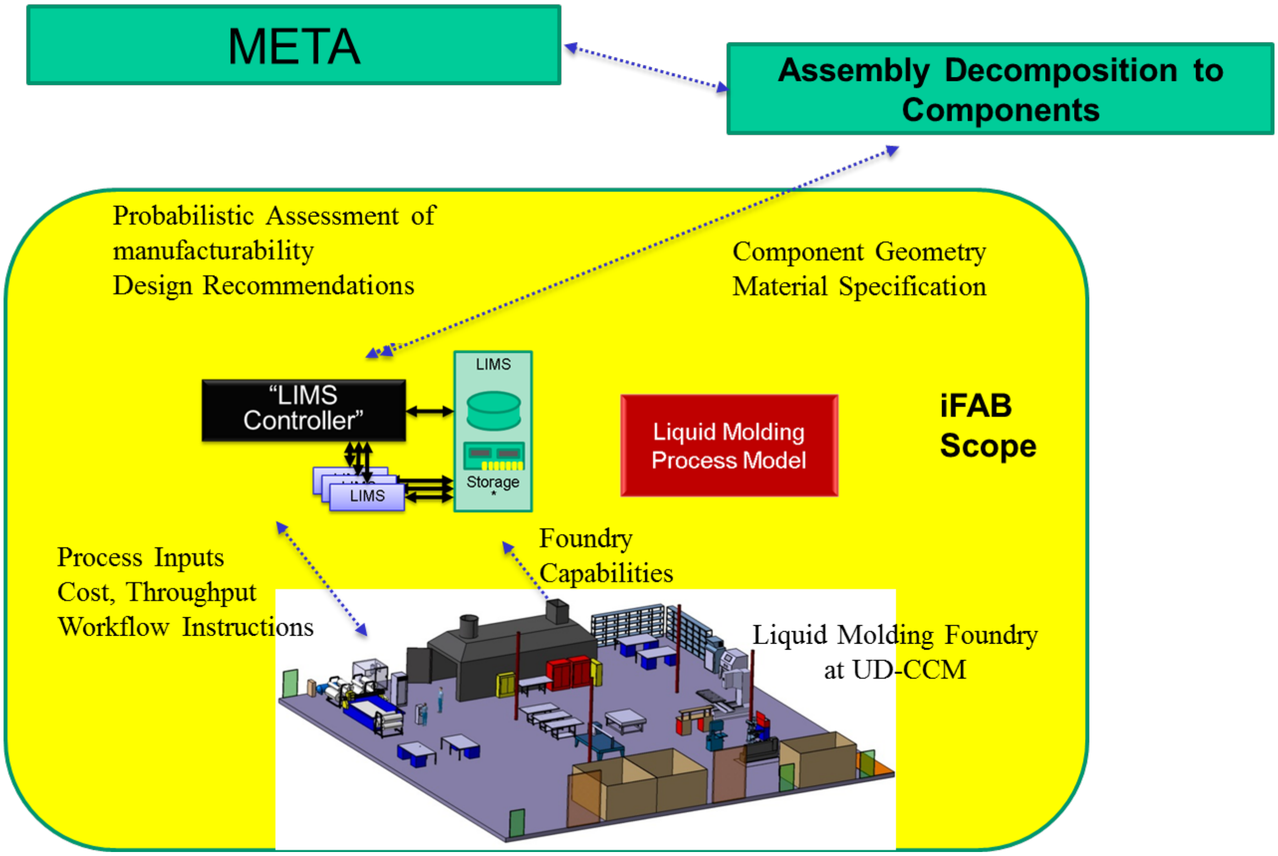


Figure 3 Overall CMES Program Flow and Relationship with META

CMES is designed to provide manufacturability assessment of individual components and not assemblies. Within the scope of the AVM program, CMES sits underneath the META design trade space. It is designed to provide automated feedback to the designer within the scope of the Other research groups within the iFAB portfolio of programs are evaluating decomposition of assemblies into individual components. Additionally, we expect majority of manufacturability assessments to be done first at the component level, prior to building component assemblies.

Manufacturability feedback to the designer has been implemented at three (3) levels of abstraction, which will be appropriate for conceptual design, intermediate design and final design. The feedback given to each of these design stages will be fundamentally different with the goal of providing the right level of information. It is further expected and desired that computational requirements for the levels of design feedback are minimal (for Level 0 – conceptual design), less than a minute (for Level 1 – intermediate design) and appropriately long (for Level 2 – final design). The first two levels of design feedback are tailored to help the designer decide whether this is a workable manufacturing process for a particular design, whereas final design feedback will focus more on quantifying process uncertainty. A Foundry Specification file provides foundry constraints for manufacturability assessment and a materials database file provides the necessary material properties for physics-based modeling (LIMS) of

the LCM process.

Feedback for Level 0 will consider the component geometric envelope, materials (fiber/fabric and resin) and the capability of the foundry in which the component is to be fabricated. Based on this low fidelity analysis we would return a simple yes/no on specific manufacturability concerns and a preliminary cost and time estimate based on experiential averages (range of $/lb or $/sq ft).

Feedback for Levels 1 and 2 will require a meshed CAD model of the component. Automated meshing is available in all CAD software tools, and our mesh requirements are simple (documented in Appendix A). At this stage of design, a "ply book" should be completed, which documents the number of fabric layers, orientation of each layer, thickness, ply sequencing nomenclature, point of origin (for reference) and principle material directions. Other material properties include fabric permeability, assumed fiber volume fraction, resin properties including viscosity and cure cycle, core (if sandwich structure) and any inserts and its attributes (such as for joint locations). If no starting process plan is provided, automated generation of process plans will occur. A number of process plans will be evaluated for the component and manufacturing metrics returned to the user. These include manufacturability for each process plan (yes/no), optimal parameters for each plan, expected volume fraction, thickness, cost and throughput. In addition, the potential impact of process uncertainty will be provided for each process plan evaluated. Design recommendations will be provided for each process plan along with a qualitative process cost impact of the proposed change.

Feedback for final designs will primarily address process uncertainty quantification for the optimal Level 1 (intermediate design stage) process plan selected. Due to the number of runs needed to realize high fidelity results, we do not anticipate real-time design feedback for this case. The Foundry Specification file will document the variability in process parameters at the Foundry, human factors that impact the process, and any other parameters that impact uncertainty in the manufacturing process. For the selected process plan (result of Level 1), a probabilistic assessment will be used to quantify and predict expected part yield, variability in manufacturing metrics (cycle time, dimensions, volume fractions etc.), and cost and throughput impact. Completion of this step generates the final build to print for the component, which is provided to the Composite Node for setup and instruction generation.

The following section documents the input specifications, with example input files.

2.2 Input Specification and File Structure

CMES requires a series of input datasets to operate. These files detail all of the requirements and limitations associated with composites manufacturing, along with some of the simple characteristics of the part. The datasets are:

- Component description (*.bdf) – the meshed geometry file in Nastran *.bdf format
- Part data (Part.xml) – documents part data, levels of abstraction etc
- Foundry data (Foundry.xml) – foundry capabilities data
- Material data (matdb.xml) – materials database

The following subsections document the data files and formats used.

2.2.1 *Component description (*.bdf)*

Component geometry is provided to CMES through a meshed geometry file in *.bdf format, which is a common data format developed by MSC Software and prevalent in both CAD and Analysis environments. The file documents the mesh data for the component in question so that it can be exported to external codes, such as CMES. While other mesh data formats can also be used, we have adopted the *.bdf format as the standard for CMES.

An example of a typical *.bdf file is shown below, the initial section documents standard mesh parameters, coordinate systems in use and material properties for the materials selected for each element in the meshed part. This is typically generated by the designer or META user after completion of the design and analysis phase, where all geometry and material specifications are complete. The bulk of the file documents the mesh nodes (GRID), elements (CQUAD4, CBEAM) and connectivity.

```
$ Finite Element Mesh - PTC - MSC/NASTRAN 2008 - 87476_MAIN_CHASSIS_D_4
$
SOL SESTATIC
TIME 60
CEND
DISPLACEMENT = ALL
SPCFORCES = ALL
FORCE = ALL
OLOAD = ALL
STRESS(SORT1,REAL,VONMISES,BILIN) = ALL
STRAIN(SORT1,REAL,VONMISES,BILIN,FIBER) = ALL
ESE = ALL
BEGIN BULK
PARAM,POST,0
PARAM,AUTOSPC,YES
$ Global Coordinate System of the model
CORD2R,1,0,0.,0.,0.,0.,0.,1.,
,1.,0.,0.
$ ----------------------------------------
$ Mesh "87476_MAIN_CHASSIS_D_4"
$ Included Components :
$   87476_MAIN_CHASSIS_D_4
$ Coordinate System for grid coordinates
CORD2R,2,1,0.,0.,0.,0.,0.,1.,
,1.,0.,0.
$ Coordinate System for default grid displacement
CORD2R,3,2,0.,0.,0.,0.,0.,1.,
,1.,0.,0.
MAT1,1,73084.4,,0.33,2.79355E-9,2.304E-5,,,
PSHELL,1,1,0.1,1,,1
PBEAM,2,1,12.5664,12.5664,12.5664,0.,25.1327,,
,0.,2.,2.,0.,0.,-2.,-2.,0.,
,YESA,1.,,,,,,,
,,,,,,,,,
,,,,,0.,0.,0.,0.
GRID,1,2,-23.,2.81013,-377.488,3
GRID,2,2,-23.,25.6231,-462.627,3
----------more GRID-------------
CQUAD4,1,1,79,21,140,78,,0.,
CQUAD4,2,1,79,70,139,21,,0.,
```

```
----------more CQUAD4-------------
CBEAM,4439,2,11,39,0.,0.965926,0.258819,,
,,,,,,,,
CBEAM,4440,2,39,40,0.,0.965926,0.258819,,
,,,,,,,,
----------more CBEAM-------------
```

2.2.2 Part.xml

Part.xml is the main input file that contains level of abstraction desired, filenames for all the input and output files (*.bdf, foundry, material, output), and is required for all levels of abstraction, as it contains all of the operating information. It also documents the units used, as well as materials selected by the designer for the part.

It begins with the level of abstraction:

```
<Query>
  <Level>2</Level>
</Query>
```

The query level to use depends on the level of feedback desired. Levels 0 and 1 are rapid responses ranging from ~seconds to ~minutes. Level 2 queries are more processor and memory intensive, as it provides probabilistic assessment of the selected process scheme. Query level is followed by the filenames for each dataset.

```
<Files>
  <BDFFile>curv_center.bdf</BDFFile>
  <FoundryFile>foundry.xml</FoundryFile>
  <MaterialFile>matdb.xml</MaterialFile>
  <OptionFile></OptionFile>
  <OutputFile>out.xml</OutputFile>
</Files>
```

At query level 0, no mesh file (BDF File) needs to be provided, however, all other files except the option file must be provided.

For level 1 and 2, a mesh file must be specified, and it must be a Bulk Data Format (BDF) file. This is a NASTRAN data format that documents mesh data in the form of nodes, elements, and connectivity and material data. It is necessary to either provide the full path to the file, or for the file to be in the same folder as the CMES executable.

Provide the unit system the part was drafted in, using all lower case. CMES currently only accepts inches, millimeters, and meters as proper tags.

```
<Units>millimeters</Units>
```

Provide the component thickness and bounding box thickness in units specified. The bounding box represents the physical dimensions of a box that would contain the part in its finished state.

```
<thickness>5</thickness>
<BoundingBox>
  <xmin>0.0</xmin>
  <xmax>30.0</xmax>
  <ymin>0.0</ymin>
  <ymax>15.0</ymax>
  <zmin>0.0</zmin>
```

```
  <zmax>10.0</zmax>
</BoundingBox>
```

Describe the weight of the part in the appropriate unit system. If the mesh is in Inches, use pounds. If the mesh is in millimeters or meters, use kilograms. Weight is primarily to assess foundry handling capability. Weight of the component should be readily calculated in the design environment, based on the materials selected.

```
  <Weight>11.00</Weight>
```

Finally, document the resin or polymer, fabric or reinforcement and core (for sandwich structures only). CMES currently uses lower case letters for the naming convention and consistency needs to be maintained in both the foundry and materials database file.

```
<Resin>
<Class>vinylester</Class>
<Label>IMT0X1C</Label>
<Cure_Temp>22</Cure_Temp>
<PotLife>15</PotLife>
<MatID>003</MatID>
</Resin>

<Preform>
<Class>glass</Class>
<Label>0F_W1NE</Label>
<MatID>001</MatID>
</Preform>

<Core>
<Class>balsa</Class>
<Label>Wood</Label>
<MatID>002</MatID>
</Core>
```

2.2.3 Foundry XML File

The foundry file documents it capability with regards to LCM processing of composites. All the parameters documented below need to be identified as part of a composites foundry database. As with the input XML file, it is recommended that the example foundry file be used and modified, rather than creating one. The overall foundry capability categories are:

- Processes available
- Operating conditions
- Racetracking parameters
- Material processing capability
- Cutting capabilities
- Handling capabilities

The foundry file begins with units specification, either IMP for imperial, or SI for metric.

```
<units>IMP</units>
```

2.2.3.1 *Processes available*

The “process_type” class contains all of the different types of processes the foundry can perform, along with the relevant data associated with them. Data to be provided is primarily part size range that can be manufactured in the foundry. Lengths, Widths, Depths and Thickness are the primary parameters. A minimum value is also necessary for Length, Width and Depth as the foundry may opt to use alternate processes for parts below a certain size. The code below shows an example for VARTM process specification.

```
<process ="VARTM">
<part_size>
      <min_length>6.0</min_length
      <max_length>500.0</max_length>
      <min_width>6.0</min_width>
      <max_width>500.0</max_width>
      <min_depth>0.0</min_depth>
      <max_depth>250.0</max_depth>
      <max_thickness>24.0</max_thickness>
</part_size>
</process>
```

While a composites foundry can have more than LCM processes as capabilities, our focus is on the following four (4) LCM variants and whether the foundry the capability available.

- VARTM
- RTM Light
- Membrane VARTM
- Center Infusion

2.2.3.2 *Operating Conditions*

The next section of foundry.xml describes the various operating conditions within the foundry. Vacuum, humidity and room temperature are all reported as an average value, with the variability (or standard deviation). Temperature is checked to make sure it remains within a 20 degree range, from 62 °F to 82 °F. One of the challenges with temperature variation is its effect on resin viscosity. Resin data from manufacturers typically is specified for 77 F (room temperature). Deviation from this temperature can cause significant changes in viscosity, leading to different process conditions. CMES currently requires viscosity data at room temperature. If viscosity data is available at alternate temperatures, this can also be used. The main assumption that limits temperature-based modeling in CMES is whether resin cure initiates as temperatures increase beyond room temperature. As long as no cure occurs, CMES can model and predict manufacturability for any temperature range.

```
<units>IMP</units>
…
```

Room temperature needs to be documented, with a variability of $\pm$ ° F. Vacuum level for the pumps or vacuum system in the foundry is documented in inches of mercury with a variability of $\pm$. inches. Humidity variability is also important and needs to be documented.

```
<vacuum>
      <!-- Level of vacuum pressure available in the foundry in units
```

```
specified -->
            <level>29</level>
      <!-- Variability of vacuum pressure in percent -->
            <variability>.04</variability>
</vacuum>

<humidity>
      <!-- Relative level of humidity in the foundry in percent -->
            <level>5</level>
      <!-- Variability of humidity in the foundry in +- percent -->
            <variability>5</variability>
</humidity>

<room_temp>
      <!-- Level of temperature in the foundry in units specified -->
            <level>70</level>
      <!-- Variability of temperature in the foundry in +- degrees -->
            <variability>5</variability>
</room_temp>
```

Resin mixing is a part of the process and operator expertise determines the potential for variability in resin viscosity and potlife.

```
<resin_mixing>
      <operator>
            <!-- Level of the operator, 1, 2, or 3-->
            <operator_level>3</operator_level>
            <!-- The variability of the resin viscosity based on the
experience of the technician in percentage  -->
            <viscosity_variability>5.0</viscosity_variability>
            <!-- The variability of the resin pot life based on the
experience of the technician in percentage  -->
            <potlife_variability>5.0</potlife_variability>
      </operator>
</resin_mixing>
```

2.2.3.3 <u>Racetracking Parameters</u>

Racetracking parameters depend on the type of racetracking edge, but all share the same structure for reporting the magnitude and probability, which is based on the operator and foundry capabilities. Operators are ranked by level from one to three, with a level one being a novice and a level three being an expert. Racetracking probabilities are associated with the level of operator, where the lower the level, the higher the probability of racetracking from this particular operator. Magnitudes also depend on tolerances in cutting, placement, tooling, and draping, and are reported in units following the example in the foundry.xml file provided.

```
<edges_outer>
      <operator>
            <operator_level>3</operator_level>
            <racetracking_magnitude>0.0</racetracking_magnitude>
      <racetracking_probability>0.0</racetracking_probability>
      </operator>
</edges_outer>
```

2.2.3.4 *Material Processing Capabilities*

For material_capabilities, list all fabrics, cores, and resins, classifying them in their respective categories that the foundry can work with. These represent materials that foundry has a history of use, and is comfortable with acquisition, handling, safety, processing and waste disposal. It is imperative that the material capability listings match the case used in the Part.xml and matdb.xml files, as a mismatch such as “Glass” and “glass” will cause an “incompatible fiber system” response from CMES.

```xml
<fabric>
      <fiber>glass</fiber>
      <fiber>carbon</fiber>
      <fiber>kevlar</fiber>
      <fiber>thermoplastics</fiber>
</fabric>
```

For the oven, specify the minimum and maximum operating temperatures as well as the maximum size of part.

```xml
<oven>
      <!-- Minimum temperature of oven in units specified -->
                  <temperature_min>65</temperature_min>
      <!-- Maximum temperature of oven in units specified -->
                  <temperature_max>600</temperature_max>
      <!-- Max length of part that can be placed in oven in units
specified -->
                  <max_length>36.0</max_length>
      <!-- Max width of part that can be placed in oven in units
specified -->
                  <max_width>24.0</max_width>
      <!-- Max height of part that can be placed in oven in units
specified -->
                  <max_height>48.0</max_height>
</oven>
```

2.2.3.5 *Cutting Capabilities and Limitations*

The cutting section of foundry.xml reports the foundry’s ability to accurately and repeatedly cut fabric to tolerance. Similar to the oven and process structures, the physical space requirements are described in addition to the tolerances and repeatability of the cutting process.

```xml
<cutting>
      <max_length>120.0</max_length>
      <max_width>72.0</max_width>
      <max_thickness>3.150</max_thickness>
      <tolerance>0.020</tolerance>
      <repeatability>0.010</repeatability>
</cutting>
```

2.2.3.6 *Handling Capabilities*

Handling capabilities primarily refers to part weight, as part geometry limits are already covered for each individual process. This refers to weight limits of handling equipment – cranes,

gantries etc.

```
<weight_limit>1000</weight_limit>
```

2.2.4 Matdb.xml

Matdb.xml provides all of the material characteristics for fiber, resin, and core materials. Every material has an ID that must correspond to the PCOMP card in the mesh file and the ID provided in the Part.xml. Again, the unit system must be specified.

```
<units>IMP</units>

<fabric>
      <!-- ID of the material. Must match with the MAT8 or PCOMP card
from mesh -->
      <ID>001</ID>
      <!-- Text description of material -->
      <description>Fiber Glass</description>
      <permeability>
            <!-- Kxx value in units specified -->
            <kxx>1.929e-011</kxx>
            <!-- Kyy value in units specified -->
            <kyy>1.929e-011</kyy>
            <!-- placeholder -->
            <kzz></kzz>
      </permeability>
      <!-- Fiber Volume Fraction of the material -->
      <Vf>0.5</Vf>
      <!-- Weight per unit area of the material -->
      <area_weight></area_weight>
      <!-- Compressed thickness of the material -->
      <ply_thickness_under_vacuum>.0025</ply_thickness_under_vacuum>
      <!-- Manufacturer of the material -->
      <manufacturer>Hexcel</manufacturer>
</fabric>

<core>
      <ID>002</ID>
      <name>balsa</name>
      <type>wood</type>
      <manufacturer>Nature</manufacturer>
      <max_temp>100</max_temp>
      <thickness>.05</thickness>
      <density>.16</density>
</core>
```

Resin information in the materials database contains multiple inputs. These include resin gel time, room temperature viscosity (or a temperature dependent viscosity lookup table), and mix recipes. Note that a single resin can have multiple mix recipes, and each mix recipe documents the component quantity and mix ratios as well as the achievable pot life for each mix recipe. This is a parameter that is necessary for the designer, so that appropriate resin mix recipes are selected to ensure part is manufacturable.

```
<resin>
```

```
      <ID>003</ID>      <!-- Identification Number for Resin system -->
      <name>510A</name> <!-- Name of resin -->
      <type>vinyl ester</type>      <!-- Type of resin -->
      <manufacturer>Ashland Performance Materials</manufacturer>
      <max_gel_time>75</max_gel_time> <!-- Maximum documented gel time
in minutes -->
      <viscosity>
            <RT_value>.400</RT_value>     <!-- RT viscosity value in
Pa*s-->
            <temp_table>
            </temp_table>     <!-- Viscosity relation to temperature -->
      </viscosity>

      <mix_recipe>      <!-- Use as many of these as needed for each
mix-->
            <temperature>18</temperature>
            <component> <!-- A component of the mixture, use as many as
needed -->
                  <name>MEKP</name> <!-- Name of component -->
                  <ID></ID>   <!-- Identification Number for component -
->
                  <quantity>2.50</quantity>     <!-- Quantity of
component (weight percent)-->
            </component>

            <component> <!-- A component of the mixture, use as many as
needed -->
                  <name>CoNap</name>      <!-- Name of component -->
                  <ID></ID>   <!-- Identification Number for component -
->
                  <quantity>0.30</quantity>     <!-- Quantity of
component (weight percent)-->
            </component>

            <component> <!-- A component of the mixture, use as many as
needed -->
                  <name>DMA</name>  <!-- Name of component -->
                  <ID></ID>   <!-- Identification Number for component -
->
                  <quantity>0.25</quantity>     <!-- Quantity of
component (weight percent)-->
            </component>

            <pot_life>15</pot_life> <!-- Pot life of the mixture in
minutes -->

      <cure_cycle>
                  <temperature> 27</temperature>
                  <time>120</time>
      </cure_cycle>     <!-- Cure cycle of the mixture -->
      <post_cycle>
                  <temperature>120</temperature>
                  <time>120</time>
      </post_cycle>     <!-- post-cure cycle time of the mixture -->
</mix_recipe>
</resin>
```

As noted above, the material IDs used must match the ones used in the PCOMP cards and the Part.xml file. It should be noted that there may be multiple mix recipes, so each one should be documented as described in the example material database.

2.2.5 Part Design and Material Data Needed

The part design and material data required for performing the manufacturing assessment of laminated composite structures should include all design features necessary to describe a part (or component) that is constructed using 2d or 3d continuous fiber reinforced fabric architectures. The architectures that are commonly used for laminate structures are stitched, woven, braided, and / or knitted broad good materials. The continuous fibers are combined to form a uni-directional, bi-directional, or tri-axial network of reinforcement. The part design features necessary to describe the composite component are as follows:

1) Nominal Dimensions – These dimensions define the bounding volume of the entire laminate part design. Typical attributes would be width, length, and nominal thickness.
2) Basic shape – This defines the curvature class which can be either flat, singly curved, or doubly curved.
3) Laminate Stack Up Sequence – The stack up sequence consists of multiple layers of one or more materials required to satisfy the functional performance requirements of the user specified composite component. The materials, in its simplest form, consists of the individual layers of broad good materials stacked up in a sequence and predetermined orientation relative to a principal material coordinate system to meet the component design specifications on a zone by zone basis. Each zone defines a unique laminate definition. A typical call out of the layup specification follows the air force design guide nomenclature denoted as: [theta1 / theta2 / theta3 / . . . theta(n)] S. Each angle is measured relative to the principal coordinate frame. There may be multiple coordinate frames per component; each conveniently located relative to some feature on the component tooling. There can be multiple layers per each angle specified. The layers can be of different thickness and material depending on the design requirements. The laminate specification can call out the total laminate definition (T) or just half of the laminate which requires laminate symmetry (S).
4) Stiffness Features – Stiffness features are required to achieve extensional, shear, and/or bending rigidity to meet deflection requirements for composite components. Stiffness is achieved by the selective utilization of advanced materials and / or geometric section. Section properties are incorporated into laminate construction either by integrally molded stiffeners (blade, hat section, z section, I section, etc.) or by the use of sandwich construction. Integration of stiffener elements and tailoring stiffness from these elements into composite panels generally require ply drops and transition of section to accomplish appropriate stiffness gradients so high stress concentrations are not developed. Load path determination is critical in properly determining where and how to place stiffness features in composite parts.
5) Strength Features – Strength features are generally accomplished by proper selection of the appropriate fiber / resin combination to meet performance requirements and are achieved by local thickening and customization of laminates around points of

attachments which require tailoring load paths by use of good laminate design. Both bolted and bonded joints are also considered during the strength assessment of composite components. It is here where inserts may be incorporated into the laminate in order to spread the load our sufficiently to sustain high point load attachments.

6) Ply Drop Offs and Ply Seaming Strategies - As pointed out in the stiffness and strength features, ply drops and strategies on how to stagger seams within a laminate are critical to good composite design. This becomes extremely important when large parts exceed the standard width of broad good materials and/or when the shear distortion of fabrics are exceeded and darting is required to alleviate buckling of fabric materials during layup. In general, draping simulation tools are required to develop these flat patterns which provide the darting and seaming strategies to provide good load transfer at these locations of material discontinuity. General rules of thumb are established via empirical testing and history of good design practices to mitigate the possibility of laminate "unzipping" at these joints.

7) Attachment Features – Anywhere local loads are introduced into composite parts there may require hardware integration for mechanical fastening or local thickening for bonded joints. Considerations of stiffness tailoring, joint efficiency, and galvanic corrosion need to be addressed in order to meet the full set of performance requirements.

8) Materials – The material property data required for the part design should include stiffness, strength, flow, and failure criterion measures in order to properly assess both the structural performance and manufacturability of the design. The individual properties required will be determined by the idealization of the physical design. For the purposes of this iFAB study it is assumed that all laminates are defined using 2D laminate shell theory. Structural performance assessment will require, at a minimum, the following composite properties:

   a. E1, E2, G12 – Modulus in 1,2, and 12 directions
   b. G13, G23 – Transverse shear modulus
   c. X^T X^C Y^T Y^C S – Axial tension and Compression, Transverse tension and compression, and shear strength
   d. K1, K2 – Permeability in the 1 and 2 directions respectively
   e. V – viscosity of the resin system

   All property data that are supplied for structural performance should ideally have B-basis allowables per the Mil-HDBK-17 standards.

2.2.6 Part Information Necessary for Manufacturability Assessment

Part information required for modeling using the LIMS software is a function of how the physical part is idealized in order to predict the manufacturability of the laminate design. iFAB currently assumes that all laminated components are represented by surface geometry. This geometry can represent either the outside mold line (OML), inside mold line (IML), or the mid-plane surface geometry. In most cases, the surface geometry can be easily extracted (if not automatically) from thin solid geometry. For geometries which are piecewise continuous, the

mid-plane surface geometry is the most suitable. It is required that this geometry be zoned into different regions representative of each unique laminate construction required for the part under consideration. As mentioned above, the laminate definition is cross referenced with these regions which capture different design features necessary to meet the performance requirements for the specific application at hand. It is necessary that all surfaces have their outward normals aligned with the outward normal of the tooling surface and in accordance with the direction of the stack up sequence as the operator would layup the plies on the tooling surface. It is also required that the part surface be meshed using either 4 node quadrilateral or 3 node triangular laminated shell elements. The meshing can be performed using FE CAD work benches for all layups which are draped on singly curved geometries requiring no shear in the fabric for complete coverage of the part surface geometry. The element normals of the FE mesh will coincide with the surface normal geometry. The element property definition should reference a material laminate and a material coordinate reference frame which aligns the principal direction of each laminate corresponding to the predefined zone definition.

The option is available in iFAB for the design to contain process related features such as infusion lines, vent lines or points, and anticipated areas where race tracking may occur. These can be incorporated manually in the part (mesh) by defining curves (or beam elements) contained within the geometric surface definition that represent feed lines, vacuum lines, or race tracking edges. If these features or not defined within the part, iFAB/LIMS will automatically define these based on good manufacturing practices.

The output from this part information specification currently is in a standard format used for defining the bulk data items which are required for doing FE analysis of composite structures known as the BDF format. This is an ASCII file format which contains nodal information, element connectivity, all material property data cards for performing structural analysis, and laminate specification (PCOMP) which references the material property card and is used for LIMS input to determine the effective permeability for each unique laminate zone. This file also contains BEAM element specification, as a user option, for defining process related parameters which over-ride the LIMS automation / recommendation of process parameters.

2.3 LCM Model Development

Process modeling for liquid composite molding is currently well advanced and LIMS, which has been developed at UD-CCM, is one of the best tools available for this purpose. Through years of research and development, LIMS has been used for a variety of purposes, from verification of manufacturing schemes to development and optimization of these and to the design of actively controlled processes. During these activities, the package has been integrated with a variety of other software tools like Matlab or Labview. On the other hand, the collaboration with engineering design programs and packages for other form of part analysis (say, structural FEA) has been limited to manual file imports of FEA analysis meshes.

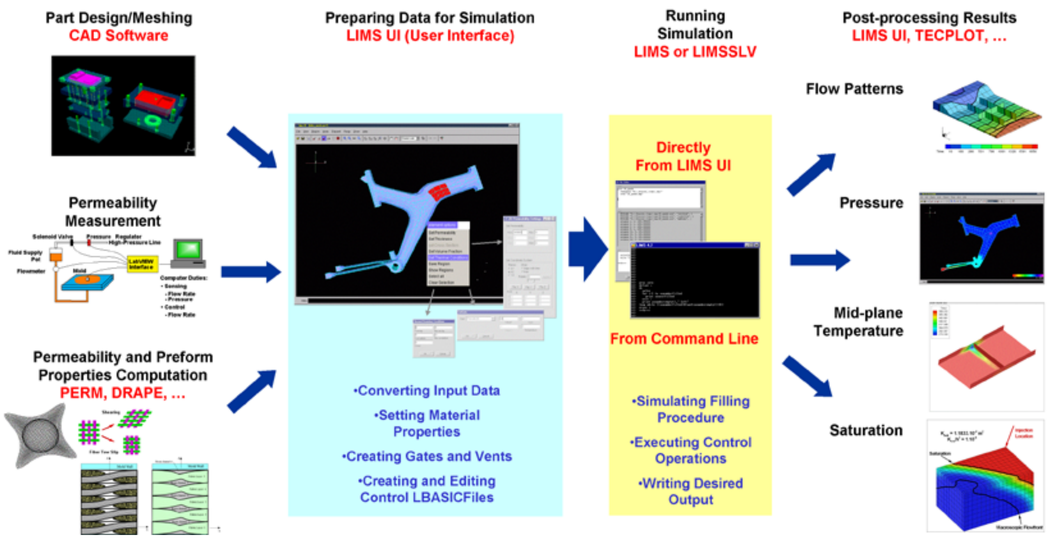


Figure 4: Resin infusion simulation using the LIMS package. The data preparation takes place in different programs and is manually imported and coupled within LimsUI. The data flow is also one-way and requires designer feedback for modification of designs to ada

The current process simulation follows the route shown in Figure 1: To simulate resin infusion and flow in the preform, one currently designs the part, exports it into the FEA program and from there exports the mesh into format that can be read by LIMS. At the same time, material properties are obtained and assigned to the model within LIMS user interface, possibly through additional filters to apply preform characteristics. The simulation results are presented in LIMS user interface or plotting program. Should there be any attempt to influence the design based on processing difficulties, this output has to be presented to designer and changes requested. This usually limits the use of process simulation within the part design process in the way the stress analysis is performed: for the verification of a given infusion design. Processing expert can still use the simulation to design or optimize the infusion scheme for existing part, but a significant level of expertise is needed to accomplish that.

2.3.1 LCM Simulation Fundamentals and LIMS Program

To simulate the mold filling, the flow of resin through fiber preforms must be modeled. This is usually described by modeling the fiber preforms as porous media. The relation between fluid pressure and averaged fluid velocity is given by Darcy's law, which states that

$$\langle \mathbf{v} \rangle = \frac{\mathbf{K}}{\eta} \cdot \nabla p \tag{1}$$

Here $\langle \mathbf{v} \rangle$ is the volume averaged flow velocity, ∇p is the pressure gradient, η is the viscosity of the fluid and $\mathbf{K}$ describes the permeability of the porous medium.

If the porous media cannot deform, as is the case in RTM process, the continuity (mass conservation) equation is reduces to

$$\nabla \cdot \langle \mathbf{v} \rangle = 0 \qquad (2)$$

The substitution of Eq.(2) in the Eq. (1), results in the following governing equation for resin pressure:

$$\nabla \cdot \left(\frac{\mathbf{K}}{\eta} \cdot \nabla p \right) = 0 \qquad (3)$$

This is elliptic partial differential equation for pressure. The boundary conditions are no flow through mold boundaries, prescribed pressure at flow front and prescribed pressure, flow rate or mixed boundary condition at inlet. The difficulty caused by the moving boundary (at flow-front) may be by-passed by using the quasi-steady approach. For low Reynolds number flow this is a viable approach. In this approach, the pressure is computed in the fluid filled porous media domain using Eq. (3). Then, the averaged flow velocity field is computed from Eq. (1). Next, the time is advanced and the flow is advanced accordingly using the time increment and computed flow velocity.

The simulation code to provide the LCM infusion model has not been developed new. The existing, well tested, package, “Liquid Injection Molding Simulation” (LIMS), developed and marketed by the University of Delaware has been used as a simulation engine. The finite element/control volume (FE/CV) solution scheme is used by this program to simulate the filling process. The solution domain is meshed with a fixed finite element mesh. Refinement in corners and similar features of stress analysis meshes are unnecessary. Control volumes are associated with each mesh node. Each control volume has a fill (saturation) factor associated with it. This factor ranges between zero (empty CV) and one (filled CV) and designates the volume of the porous media filled with the fluid. The pressure in the empty control volumes is known to be equal to that of the vent or void pressure, as the program can tracks voids and their volume/pressure change. The pressure in the filled control volumes is evaluated by the finite element method. Then, the flow between individual control volumes is determined using the computed pressure field and Eq. (1).

Once the flow rates are known, flow is advanced by explicit integration in time domain. The time step is selected so as to fill at least one additional control volume. This changes the fluid domain and hence the boundary conditions. The pressure solution is sought for the new domain and this process is repeated until the complete porous medium is saturated.

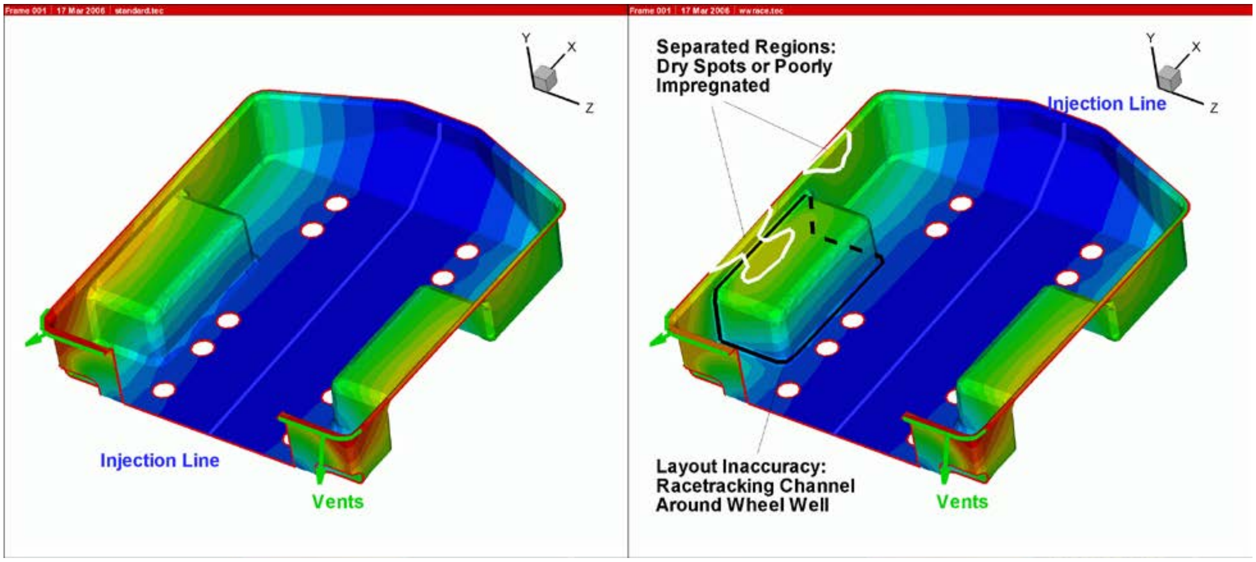


Figure 5: LIMS flow simulation of infusion of trailer – base scenario compared to a flow with disturbance over one wheelwell.

LIMS allows one to combine 1D, 2D (and 3D) elements, thus making representation of usual flow disturbances, such as improperly filled corners where resin flows much faster than in the bulk preform (racetracking channels) simple. The disturbance (and infusion and venting tubing) thus can be added to the existing mesh rather simply. Example of undisturbed and disturbed flow is in Figure 2.

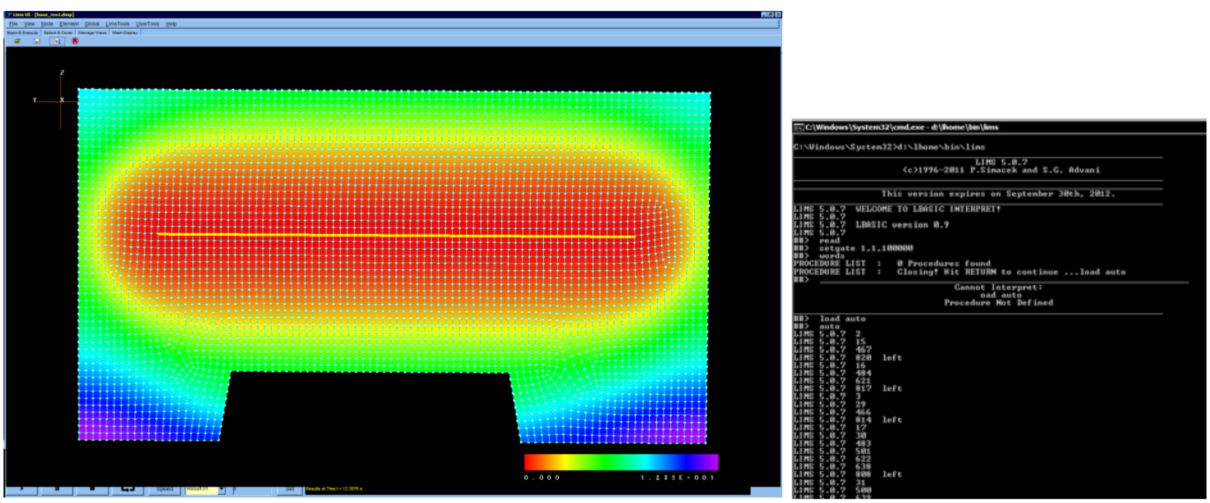


Figure 6: LIMS Graphical user interface showing flow in a panel, and command line engine running simple simulation.

LIMS package consists of the simulation engine – either command line driven or as a dynamically linked library, graphical user interface and a set of tools for mesh conversion. The graphical user interface (Figure 3) is not a part of the final product in this project but has been utilized for development/debugging purposes extensively. The simulation engine is driven by a simple scripting language (LBASIC).

2.3.2 *Modeling the Distribution Media in LCM*

LIMS can model the through the thickness flow effects of distribution media utilizing three-dimensional model [1]. This allows investigation of the lead length effects and detailed venting design, but comes at a significant performance penalty.

For optimization purpose, the two-dimensional model is more efficient. In this case, the distribution media layer should be included in the layer definition of the mesh, and can be added to the “effective” permeability computed from the weighted sum of layer permeability values [2]. This is applicable for both the throw-away distribution media on surface (as used in VARTM) and for the interlaminar distribution media common in RTM light preform. If the distribution media is applied only to a part of the surface, the layer definition should be augmented properly.

Note that the through-the thickness flow lag is lost with this modeling approach. This may be of major concern for thick parts, though for modestly thick laminates the introduced inaccuracy is acceptable.

2.3.3 *Composite Manufacturability Evaluation Software (CMES)*

It is possible, for a sufficiently qualified person, to analyze the infusion process from LIMS using its command line and GUI interfaces and some additional tools available with LIMS. However, to fully harness the ability to simulate the LCM infusion process, “Controller” software is needed to automate the whole task of process analysis. Its tasks are rather extensive, as it has to accomplish numerous things:

1. Communication with the environment, mostly by reading and writing files in predefined formats.
2. Feasibility analysis (level 0) of problem before actual flow modeling is performed. This essentially eliminates the elementary conflicts that would make the manufacturing impossible regardless of the flow nature.
3. Conversion of the input files – in BDF and XML format – into binary representation of mesh and material data suitable for simulation.
4. Generation and of model infusion layouts for various considered LCM variants and attaching the layout data to model.
5. Generation of flow disturbances according to external settings and inclusion of these in model representation.
6. Execution of all the simulation tasks in efficient way.
7. Processing the output to select the infusion scheme (level 1) and evaluate the yield rate (level 2) and whatever output is desired.
8. Cost evaluation based on modeling results

The dataflow for this program is shown in Figure 6.

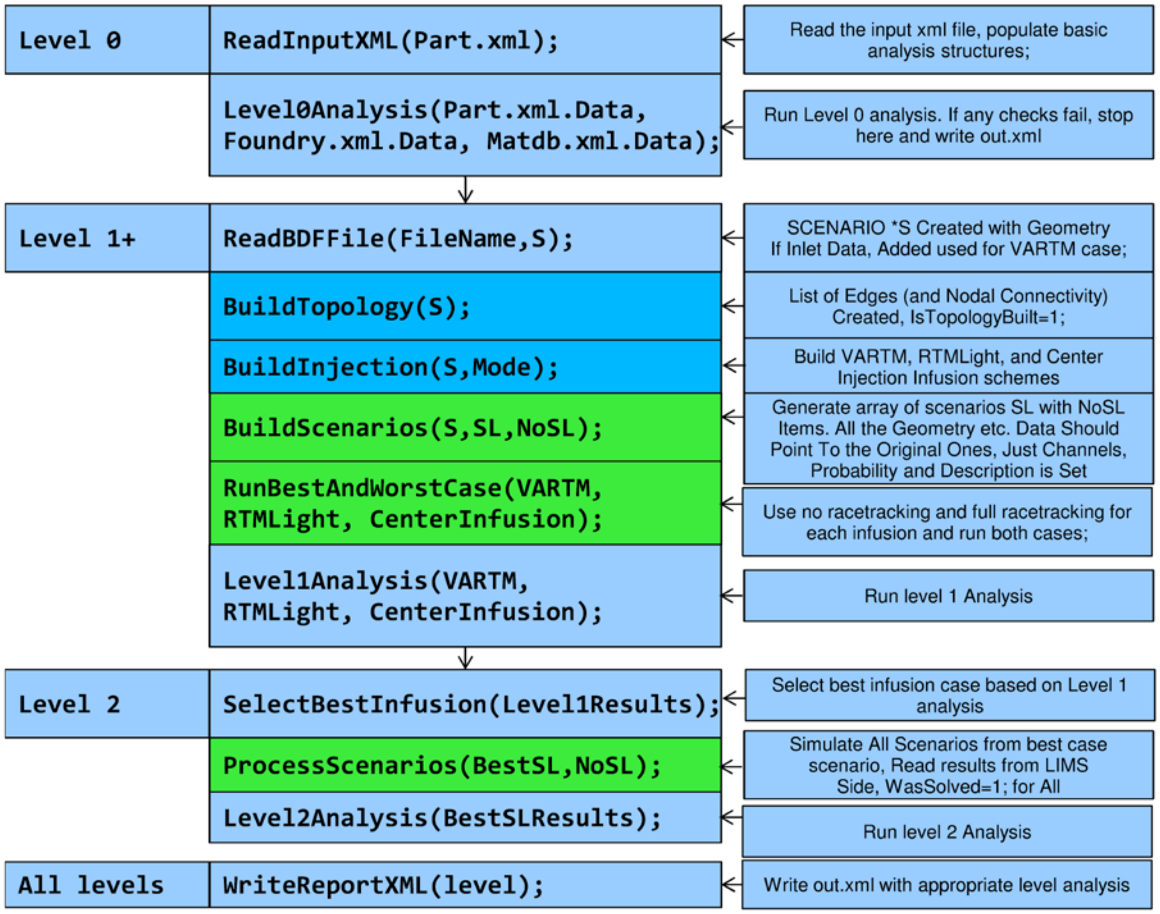


Figure 7: CMES program data flow.

2.3.4 LIMS application in CMES Engine

There are several ways to integrate LIMS as a simulation engine, with variable level of control over the LIMS execution. LIMS solver may be embedded in other programs, giving the program full responsibility for simulation, as the scripting interpreter is bypassed in this way. Tight integration may be also achieved using special dynamic link library and shared memory to pass commands and input/output data to LIMS, The latter option was typically used for LIMS integration in the past.

To integrate LIMS with CMES, looser coupling was selected, using the shell execution of command-line LIMS interface and passing the commands and data through the file-system. While this approach essentially eliminates interactive control of LIMS, but that is not needed here: LIMS is just simulating the process. On the other hand it offers several advantages when running many simulations: memory usage is more conservative as the data exchange goes through file system and it is easy to parallelize the simulation to use multiple CPU cores of current computers.

The integration of LIMS simulation engine within the process analysis is as shown in Figure 7. LIMS copy or copies are essentially performing as a child process to the controller

(CMES program) and exchanging bulk data through file system.

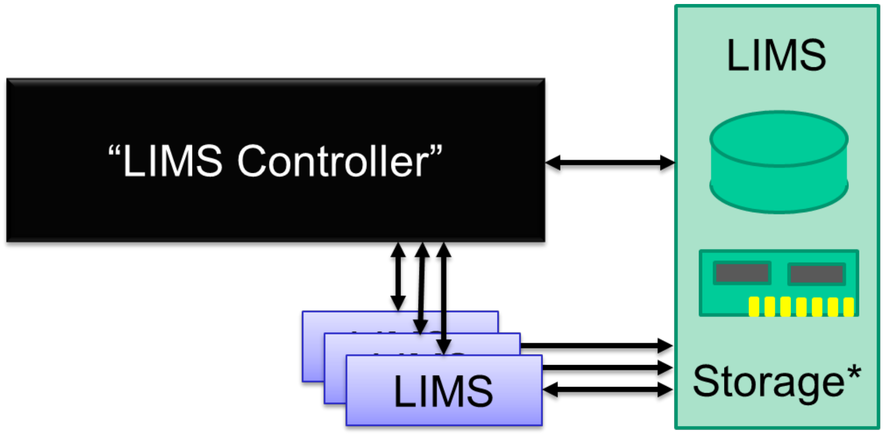


Figure 8: LIMS integration with “LIMS Controller,” in this case CMES, for Process Analysis.

The controller, written specifically for this project, provides two files to each LIMS process:

i. The mesh data representing the problem scenario, including the infusion plumbing and whatever flow disturbances are to be tested. This has been written in LIMS native format.

ii. Short script that will execute the simulations needed to evaluate the scenario. The script contains the necessarily commands to read data files, set infusion gates, run the simulations and save the result data to the disk. Last command terminates LIMS, freeing memory and CPU for the next simulation.

The controller then executes the simulation engine with proper parameters to read and execute the script file. Multiple simulation engines can be executed simultaneously to utilize multi-core computers efficiently. The LIMS results are stored in files. The controller accesses the result files after the simulation finished.

This way, the LIMS engine itself has been largely unmodified in this project. Minor additions and corrections to LIMS were necessary to facilitate the automated void analysis, as the existing way relied on user interaction with the simulation, which proved problematic in this environment. The controller functions were newly written from scratch to:

1) Convert the internal part representation into LIMS mesh.
2) Generate the necessary scripting file.
3) Execute the simulation.
4) Processes the results and convert them to internal representation for further analysis.

2.3.5 Automatic Inclusion of Process Variability

Process variability is addressed through probabilistic modeling of parameters, with particular focus on racetracking, material and process parameter variation.

Racetracking channel generation

Flow disturbances are very likely to occur on the outer edges, fabric folds (around sharp corners), and the bifurcation lines (such as rib roots) of the part. At these edges the irregular cuts and placement of preform as well as poor reinforcement compliance to the surface may result in gaps. These gaps provide flow channels of higher permeability compared to preform, making the resin flow go faster along that particular edge and modifying the flow patterns. This phenomenon has been coined as racetracking and is very commonly observed during fabrication of composite structures that use liquid composite molding process for manufacturing.

Therefore, it is necessary to detect the possible racetracking features from the mesh geometry, and assign them racetracking properties (as opposed to the bulk material ones).

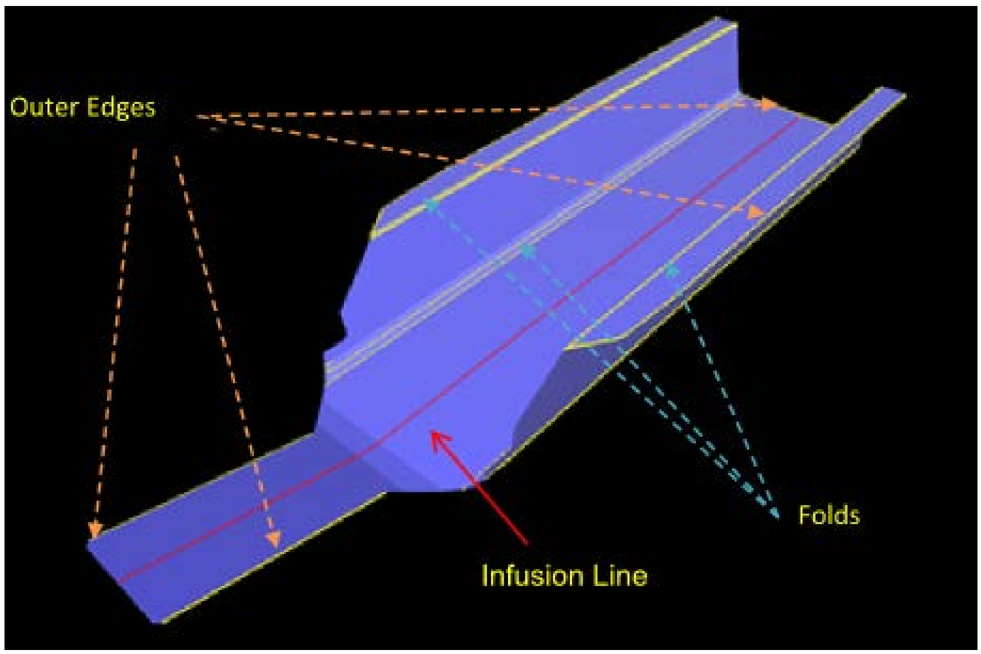


Figure 9: All racetracking channels detected for the chassis

Based on the BDF file, potential racetracking channels are detected according to the following criteria:

i. Outer edges: those edges are not shared by multiple elements and this information can be easily read from the mesh data structures (obtained from the BDF files).

ii. Folds: These are inner edges shared by exactly two mesh elements. On 2D meshed surface, the detection is possible as the angle between these elements (between their normal directions) is "large". The actual magnitude of the critical angle change is related to the radius of curvature (evaluated from angle difference and element size) and the preform thickness (as thinner preforms conform to the radius more freely). The restriction can be evaluated as

$$h/R<C$$

in which h is the fiber preform thickness (or element thickness in the mesh file), R is the curvature of the turning surface, and C is the critical number which can be preset according to experience with the particular materials.

iii. Bifurcations: These are essentially joints. These edges that are shared by more than two elements, for example rib roots. In actual layup, these would generally represent one or more folds.

Outer Edges and Folds are shown in the Figure 5.

After all the required element edges are selected, the connectivity relations among these discrete edges are analyzed to form a series of single independent channels, with the parallel edges appended to for a single edge. Thus, the geometry is augmented by a discrete set of channels which may – or may not – provide a racetracking pathway.

Creating the possible scenarios

Besides the geometric considerations, the preform preparation and placement greatly affects the degree of created racetracking. The actual racetracking strength will be variable, but some statistical description is possible. This depends (a) on the part geometry and (b) on preform manufacturing and placement within individual foundries. The probability distribution function will be discretized – for example, if we discretize it into three step values, the edge may experience no, low or high racetracking, each with different probability of appearance. Outer edges, folds, and bifurcation lines may have different distributions. This information ideally should come from the designer or manufacturing experience.

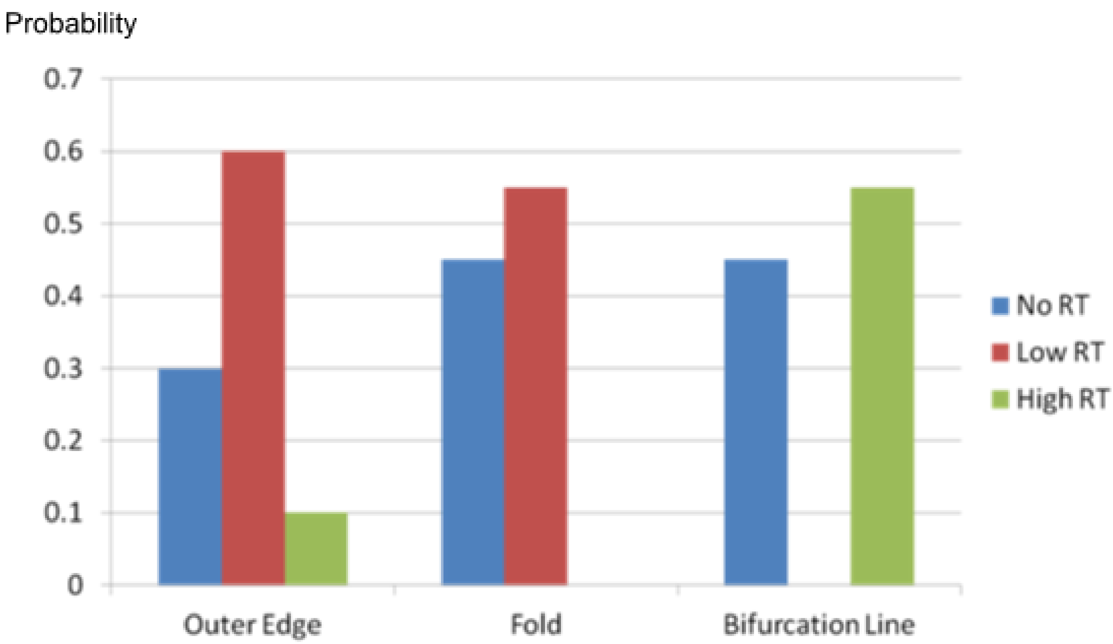


Figure 10: An example of racetracking strength distribution

The cross section area of a racetracking channel reflects the racetracking strength. The number of this cross section area varies following a probability distribution pattern, which is provided in the foundry file. Larger area means a stronger racetracking effect, and smaller area means otherwise. If the channel cross section area is zero, then no gap exists between the fiber and the mold, and hence no racetracking will be presented.

By discretizing racetracking strength probability distribution into several independent different racetracking strengths with a probability, one can build a list of combinatory scenarios,

each of which is with a certain probability. However, too many discretization of the probability distribution may result a too large number of scenarios to run. But if we assume the edge will only either no, low or high racetracking strength, scenario numbers can be controlled with a reasonable scale. For example, suppose 5 outer edges show no, low or high racetracking with certain probabilities, and 4 bifurcation edges show no, or high racetracking with another set of probabilities, then these nine channels reveal 3^5 * 2^4 = 3888 possible scenarios.

Approaches to keep scenario number low

As is shown in the example above, keeping a coarse racetracking channel strength probability will keep the scenario number within a reasonable scale. However, increasing number of racetracking channels expand the family of possible scenarios exponentially. To keep the scenario number low, it is necessary to limit the independent the number of independent racetracking channels to a reasonable scale.

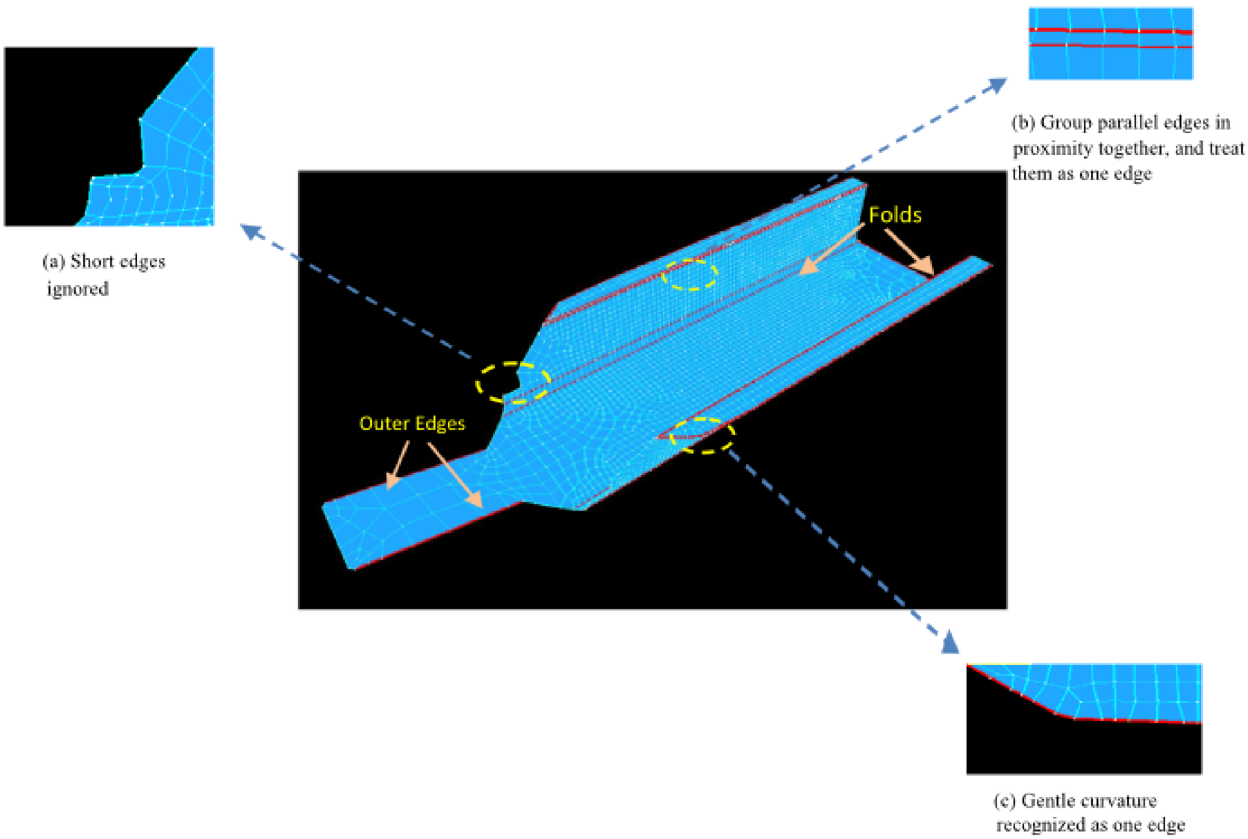


Figure 11: Racetracking channel recognition which is likely to cause changes in flow pattern during infusion.

Some of the channels are too short to have significant effects on the flow pattern, so these channels are discarded. On the other hand, when some of the edges are parallel and sufficiently close, they can be grouped together to reduce the number of permutations of the simulations to perform. Finally, some of the channels may be broken up due to irregularities in the mesh, but they should be still considered as one channel as long as this turn angle is due to an irregularity in the mesh instead of an actual geometry change.

Handling material and process parameter variability

Besides of imperfections in preform layup, LCM materials inhibit certain variation of their material properties. For example, preform permeability is generally known only within certain range. More importantly, many resin systems exhibit strong viscosity variations with temperature, while the temperature of processing is known only to be within certain bounds.

These factors, fortunately, play mainly the role of scaling the process time and do not influence the flow-front shape development. Thus, the venting is independent of these variations. They must be however considered for (a) timing of the manufacturing operations and (b) determining the suitability of resin based on pot life compared to the predicted infusion time.

2.4 Manufacturability Feedback

2.4.1 Initial Estimate Approach (Level 0)

At level 0, only a rudimentary analysis is implemented on the geometric limitations of the foundry and the basic fiber and resin properties. Simple Boolean comparisons between the foundry capabilities (weight, size, structure thickness, temperature, humidity, vacuum level, etc.) and the processing needs and geometric description and of the part are made and used to generate the output XML file for this level. Also evaluated is the time to fill the longest dimension of the part based on Darcy's Law, which is then compared to the selected resin system's gel time.

It is important to note that for all levels of abstraction, the level 0 analysis is performed, and no further analysis is performed until all of the tests at level 0 are passed.

LEVEL 0

Query	Response	Reason (if no)	Process Recommendation	Design Recommendation	Status
Can the foundry handle selected reinforcement?	Y/N	Foundry has no experience with reinforcement	Return list of reinforcements foundry can handle	Change Reinforcement	R/Y/G
Is reinforcement in fabric form amenable to infusion processes?	Y/N	Permeability too low for infusion	NA	Return fabrics that can be infused	R/Y/G
Can the foundry process the selected resin/polymer?	Y/N	Foundry cannot process polymer	Return list of polymers foundry can handle	Change polymer	R/Y/G
Are reinforcement and resin compatible?	Y/N	Reinforcement not sized for resin	NA	Select fabric that has compatible sizing with resin	R/Y/G
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Y/N	Resin pot life insufficient for part size	NA	Change resin to longer pot life system	R/Y/G

If applicable (resin needs heating to cure), are there ovens large enough?	Y/N	Oven is not large enough	NA	Design component in smaller parts, select a room temperature resin or build oven around part	R/Y/G
If structure has core, can core handle resin cure or post-cure temperature?	Y/N	Core max use temperature is less than resin cure temperature	NA	Select higher temperature core or lower cure temperature resin	R/Y/G
Are dimensions within foundry limits?	Y/N	Too large for foundry	NA	Design component in smaller parts or change foundry	R/Y/G
Can foundry handle part weight?	Y/N	Too heavy for foundry to handle	NA	Design component in smaller parts or change foundry	R/Y/G
Is the fiber volume fraction possible with foundry processes?	Y/N	Volume fraction out of range of foundry capability	NA	Return volume fraction range of foundry and use this in design	R/Y/G
Are the dimensional tolerances achievable with reinforcement, polymer and foundry processes?	Y/N	Tolerances not achievable	Use matched-die tooling and appropriate processes	Return tolerance ranges of foundry	R/Y/G
What is the rough order of magnitude cost for the part?	$$ or N/A	N/A if any of above queries return N response	NA	NA	R/Y/G

Figure 12: Structure of level 0 output

2.4.2 Level 1 – Process Variation Comparison

At level one, the part geometry is analyzed through the mesh file and used to determine possible processing disturbances that will affect the filling time and the success rate of the finished part. Next, infusion lines are generated for the geometry. If an infusion is specified in the mesh file, it is used as the VARTM infusion; else the longest detected edge is used. RTM Light uses the perimeter of the part as an infusion line, and the Center Injection method uses the geometric center of the part, based on the x and y (length and width) coordinates. Next, each infusion case has its topology analyzed; all potential racetracking regions are identified and returned as a map. Each infusion scenario is then run through LIMS twice: once with no race tracking, and again with every race tracking region active. After the results are calculated and stored, a simple formula is used to determine the best infusion scenario, optimized for fill time.

$$Cost = \left(0.4 * T_{cycle}\right) + \left(0.3 * N_{racetracking}\right) + \left(0.2 * N_{vents}\right) + \left(0.1 * L_{infusion}\right)$$

Where

$$T_{cycle} = Cycle\ Time$$

$$N_{racetracking} = Number\ of\ Racetracking\ Locations$$

$$N_{vents} = Number\ of\ vents$$

$$L_{infusion} = Length\ of\ infusion\ line$$

This optimizes the choice of infusion based on both feasibility and ease of manufacturing.

Process Scheme	**Cycle Time**	**Number of Vents**	**Cost**	**Cost Function Ranking**
VARTM				
VARTM with Disturbances				
Center Infusion				
Center Infusion with Disturbances				
RTM Light				
RTM Light with Disturbances				
Membrane VARTM				
Membrane VARTM with Disturbances				
***Optional**				

Selected Process Scheme based on Cost Function	Name

Query executed on selected process scheme	**Response**	**Reason (if no)**	**Process Recommendation**	**Design Recommendation**	**Status**
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Y/N	Resin pot life insufficient for part size	NA	Change resin to longer pot life system, or design in smaller components	R/Y/G
What are the number of vents to completely fill part?	Number		If > 5, method not recommended	TBD	R/Y/G

Cost Function	Cycle time*	Number of vents	Number of Racetrack locations	Length of infusion line
Importance	1	3	2	4
Weight	40%	20%	30%	10%

Figure 13: Level 1 output format

2.4.3 Level 2 Success Probability

Processing the scenarios

Before running this level, each scenario in the list has an infusion line and a series of racetracking channels, both of which are written in the mesh file in the form of bar elements. Also, material properties are either read directly from the original BDF file or are calculated when interpreting the data. Then LIMS is called to simulate the infusion process for each particular scenario.

Two different simulations are executed for each specific scenario. The first one assumes the mold to be under perfect vacuum (corresponding to the membrane VARTM), such that the resin can saturate the entire preform and all the volatiles are able to escape through the membrane from wherever they are captured. Filling time for infusion with correct venting arrangements is easily obtained from this simulation, but the venting scheme and potential defective areas are not obvious for automatic processing, though a skilled analyst will pick them from the post-processing data.

Therefore, it is necessary to conduct a second simulation on the same scenario, which can predict the regions in the geometry that are likely to be separated from vents and remain partially dry. This second simulation sets a non-zero volatile pressure in the mold. This volatiles are compressed by the resin filling the mold, and the simulation stops when the trapped volatile pressure reaches the resin pressure. All the volume left unfilled is recognized as the last region to fill where the vents should be located. The filling time results from the second simulation can be inaccurate because of the raising volatile pressure slows the flow, though, should the vent be correctly placed, the pressure increase will not happen. Hence the first simulation gives us the time to fill and the second simulation for that scenario identifies the regions and the size of the regions that filled last that must be processed for venting design.

Number of Vents	Yield
1	
2	
3	
N	

Recommended number of Vents	

1-vent scenario histogram

Process Parameters	% of failed parts
Folds	
Edges Inner	
Edges Outer	
Bifurcations	
Material properties	
Vacuum	

Temperature	

	Average	STDEV
Cycle time		

Cost	Number

Figure 14: Level 2 output format

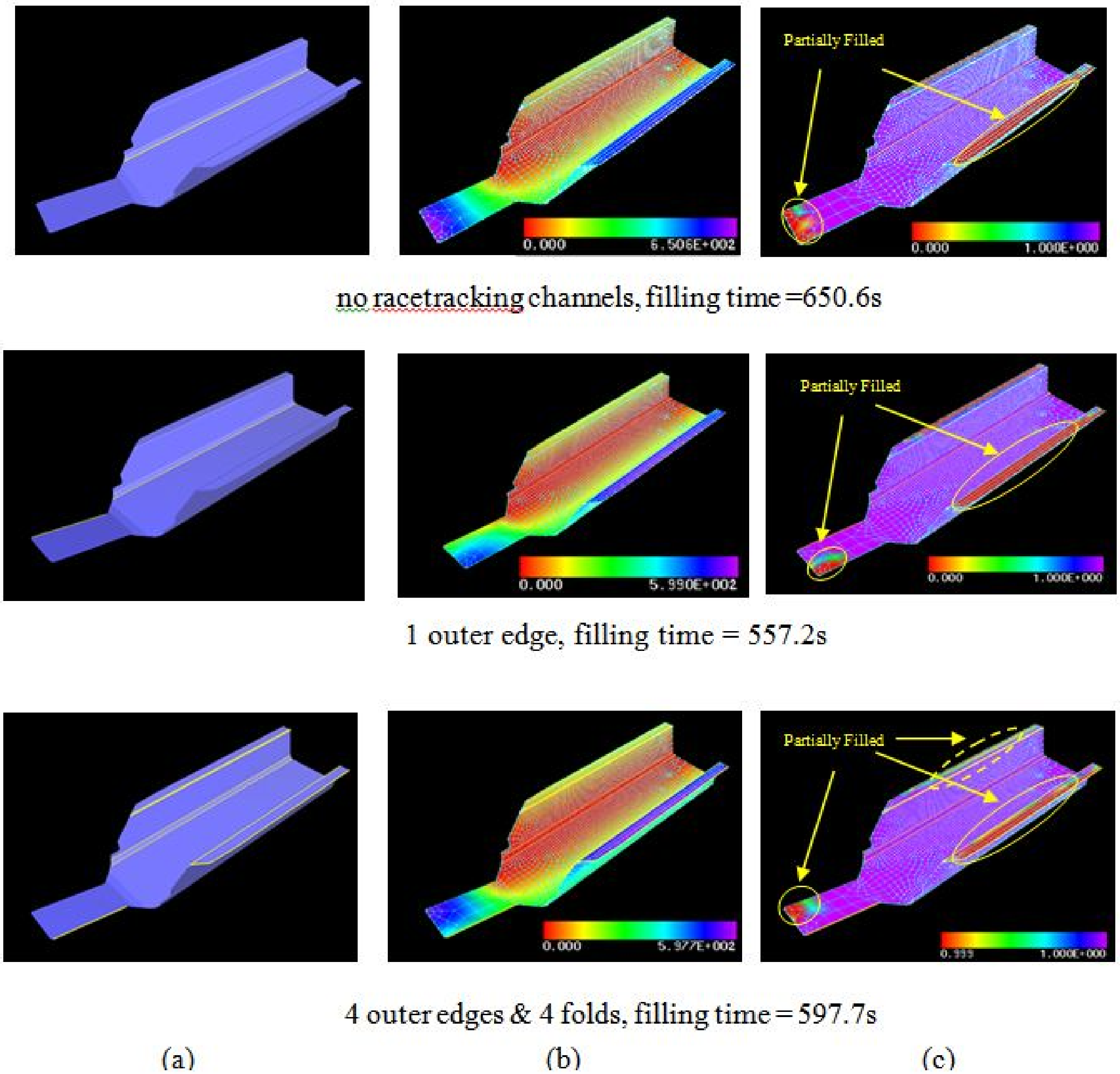


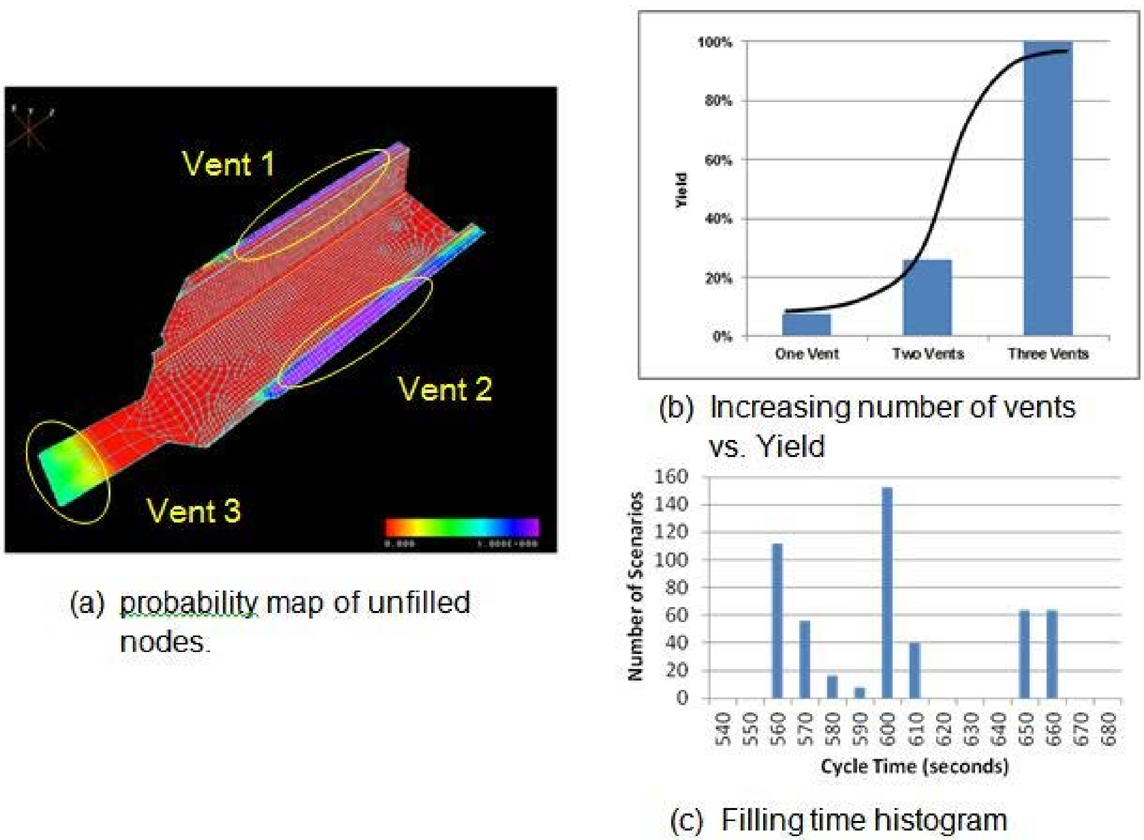
Figure 15: Three sets of results with infusion line selected by the program as shown in Figure 6a; (a) racetracking channels distribution; (b) filling time and flow pattern (c) fill factor distribution clearly showing regions with partially filled nodes

After running all the permutation of scenarios in LIMS, results are then recorded into

each scenario's RESULTS section. Results information for each scenario includes total filling time, nodal filling time, nodal pressure and fill-factor (resin saturation within node location) when the simulation is completed. All these results are available for further analysis.

Evaluating Probability of success

It is reasonable to select those areas that are most likely to be unfilled as vent locations. To find the areas that are most likely to be unfilled, all the scenarios' results are considered. First, for a specific scenario, all the nodes with a fill-factor less than 99% are recognized as unfilled. Each of these nodes is weighted with the scenario probability. These probabilities are superimposed for all the scenarios. This produces a probability map which denotes the probability for each node to remain unfilled. Those nodes with the highest probabilities of being unfilled should be set as vents. One should also factor in the area as a larger unfilled region with lower probability as that could also be a likely candidate for a vent.



(a) probability map of unfilled nodes.

(b) Increasing number of vents vs. Yield

(c) Filling time histogram

Figure 16: Results - Vent locations, yield as a function of number of vents and fill time distribution for 512 scenarios

Having created this unfilled region map in terms of nodal unfilled probabilities, the next step is to group the adjacent nodes together to determine the number of separate groups, as each of these will require separate vent. Depending on number of allowable number of vents, vents will be assigned to the groups with highest probability and the probability of groups remaining

without vent gives the probability of process failure. Thus, with sufficient number of vents one should be able to achieve 100 % success (yield), but for limited number of vents the number is lower.

Sensitivity analysis is then conducted to see which racetracking channels are contributing the most to part failure. If the yield is less than 100% for the minimum number of vents (1 vent), some of the scenarios have failed. The failed scenarios are evaluated and a log of which racetracking channels are involved, is maintained. These racetracking channels are separated into outer edges, folds and bifurcation lines, and the racetracking channels that appear the most frequently in the failed parts provide an assessment of channel sensitivity to yield.

2.5 Process Planning and Cost Modeling

Liquid Molding manufacturing processes can be broken down to a series of eight work centers. The work centers are listed in order of work flow:

Cutting – This work center brings the raw materials in from storage and the flat patterns for all materials which are needed for a given part are cut. Cutting operations, both manual and CNC, are carried out based on a part traveler's instructions.

Kitting – Once all flat patterns have been cut they are organized into "kits" of materials needed to fabricate one or more parts. In each kit the fabric is organized according to the ply table and stacking sequence as well the process aid materials which were cut are placed in the kit.

Pre-form Assembly – When a part requires additional materials such as bonded in inserts added to the kit or the need to attach plies together prior to loading into the tooling those operations are carried out at this point.

Molding – At the molding stage all the materials are loaded into the tooling and preparations are made for the infusion including the placement of the vacuum bag, infusion lines, and vacuum lines. The resin is mixed at this stage and the part is then infused.

Post Processing – Once the part is cured it is removed from the tool and lightly cleaned of any flashing. Any additional machining to the part is done at this stage in the process such as drilling or trimming.

Quality Control – The part is then inspected for critical dimensions and a report is generated documenting the results. At this point the part either moves on or is evaluated for correction. If out of tolerance and the part cannot be corrected it is then discarded.

Assembly & Integration – The final assembly of the part is performed at this center. If the part requires additional bonded in components such as threaded inserts this happens prior to final assembly.

Final Quality Control – Once the part has been integrated into its final assembly it is then inspected or if there is no final assembly the part is inspected on its own and a report is generated prior to shipment.

In order to perform cost analysis on a per part basis time was tracked from work cell to work cell on the task level. Time taken to complete a task was recorded by each technician and/or operator performing the work. The data was then collected in a spreadsheet with rates assigned to each resource. For personnel time was tracked and rates assigned as an hourly rate.

For equipment resources estimates were assumed on an hourly rate as well. Materials were broken down to rates on a linear foot basis. If additional subcontracts or services would be needed the dollar amounts would be entered as needed.

Work Cell	Labor Hours	Subcontract	Direct	OH	Mfg Cost	Prod Cost
1 - Cutting						
Clean up	0.5		$ 12.50	$ 6.33	$ 18.83	$ 18.83
Cutting fabric	4		$ 100.00	$ 50.60	$ 150.60	$ 150.60
Process aid cutting	2		$ 50.00	$ 25.30	$ 75.30	$ 75.30
(blank)						
2 - Kitting						
Preform Kitting	0.5		$ 12.50	$ 6.33	$ 18.83	$ 18.83
4 - Molding						
Clean up	0.1		$ 2.50	$ 1.27	$ 3.77	$ 3.77
Dispense & mix resin	0.75		$ 18.75	$ 9.49	$ 28.24	$ 28.24
Infusion	1		$ 25.00	$ 12.65	$ 37.65	$ 37.65
Preform layup	2		$ 50.00	$ 25.30	$ 75.30	$ 75.30
Process aid placement	1		$ 25.00	$ 12.65	$ 37.65	$ 37.65
Tool prep	0.5		$ 12.50	$ 6.33	$ 18.83	$ 18.83
Vacuum bag preform	1		$ 25.00	$ 12.65	$ 37.65	$ 37.65
5 - Post_Processing						
Demolding	1		$ 25.00	$ 12.65	$ 37.65	$ 37.65
Post-cure		$ 400.00	$ 400.00	$ -	$ 400.00	$ 400.00
Profile trimming	2		$ 50.00	$ 25.30	$ 75.30	$ 75.30
8 - Final_QC						
Finished part weighing	0.25		$ 6.25	$ 3.16	$ 9.41	$ 9.41
Thickness measurements	1		$ 25.00	$ 12.65	$ 37.65	$ 37.65
(blank)						
Grand Total	17.6	$ 400.00	$ 840.00	$ 222.64	$ 1,062.64	$ 1,062.64

Figure 17: Example of cost analysis for a 3' x 6' curved panel

2.6 Output Specification

CMES output format examples are shown below:

Example of a successful level 1 run:

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

Failure Example:

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	No	Predicted fill time too high for resin pot life.	Choose a different mix recipe, make a smaller part, use a part with higher permeability.	NA	Red
If resin needs heating to cure, are there ovens large enough?	No	Predicted fill time too high for resin pot life.	Change part into a combination of smaller parts, select a different foundry, or build an oven around the part	NA	Red
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	No	Fiber Volume Fraction too high for liquid molding	Reduce Fiber Volume Fraction in design.	NA	Red

Example of a successful level 1 run:

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking	Process Scheme*	Flow Pattern*
VARTM	320.414	2	NA	119	NA	NA
VARTM with Disturbances	264.1	2	NA	119	NA	NA
RTM Light	262.421	1	NA	83	NA	NA
RTM Light With Disturbances	145.56	1	NA	83	NA	NA
Center Infusion	3625.11	2	NA	1313	NA	NA
Center Infusion with Disturbances	2931.33	4	NA	1313	NA	NA

Selected Process Scheme based on Cost Function:	RTM Light

Example of a Successful Level 2 run:

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking	Process Scheme*	Flow Pattern*
VARTM	320.414	2	NA	119	NA	NA
VARTM with Disturbances	264.1	2	NA	119	NA	NA
RTM Light	262.421	1	NA	83	NA	NA
RTM Light With Disturbances	145.56	1	NA	83	NA	NA
Center Infusion	3625.11	2	NA	1313	NA	NA
Center Infusion with Disturbances	2931.33	4	NA	1313	NA	NA

Selected Process Scheme based on Cost Function:	RTM Light				
Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
What are the number of vents to completely fill part?	1	NA	NA	NA	Green

Number of Vents	Yield
1	100%
Recommended Number of Vents	0

	Average	STDEV
Cycle Time	200.288	155.969

Process Parameters	% of Failed Parts
Outer Edges	0
Folds	0
Bifurcations	0

2.7 Assumptions and Limitations

CMES is based on the physics-based model LIMS, which has several inherent assumptions to simplify the modeling process for complex geometries. These are listed below:

- Flow model is two-dimensional
  - One-dimensional channels are used to model infusion hardware and racetracking.
  - Three dimensional effects of flow lagging under distribution media are neglected.
- Resin distribution tubing (on part surface) is modeled
  - Connecting tubes are not (problem if small)
- Material properties are assumed known and constant
  - Effective permeability is assembled from ply layup if available.
    - Can handle complex draped layups
  - Variation in permeability (including temperature dependent) and viscosity are covered by a time scaling factor

- Captured volatiles are assumed to behave like ideal gas
  - No volatile source in resin
- Effect of improperly designed venting on flow is not considered (worst case scenario for failed cases)

2.7.1 CMES Modeling Requirements

To ensure CMES executes correctly for complex geometries, the following modeling requirements should be met.

- Moderate mesh density is recommended (to save execution time).
- Preform draping doubly curved surface changes orientation from place to place. This in turn changes the local material properties (may be significant). The model cannot capture this unless the draping has been simulated and put into PCOMP cards of BDF mesh (by Fibersim or other software)
- Material data in each element is constant. Thus, ply drop-offs should happen between elements.
  - To properly model this, lines of any ply-drop-offs should be mapped on the surface and meshed properly.
- Addition of infusion tubing works best if the desirable lines are mapped as lines on the mesh
  - This will be automatic for outer edge
  - Inner infusion line locations (such as lines of symmetry) should be added to meshed geometry to generate straight lines in the mesh.
- Edge detection – particularly fold detection – depends on recognition of fast curvature changes. This can be ensured by
  - Refining elements follow the change of curvature closely (say each element twisted by no more than 15 degrees)
  - Or, planting a line of nodes along the fold to ensure coarse elements do not bridge the fold

2.7.2 CMES Hardware Requirements

Computer hardware requirements to execute CMES are as follows:

- LIMS simulation engine is a single threaded application
  - Multiple simulations can be run at once on separate cores
    - Memory requirements of each LIMS instance are modest (for moderate size mesh, say 5,000 elements) Massive number of temporary files may be written (~ 4 x number of scenarios)
- Requires at least 4 Gigabytes of RAM.
- Dual core processor at minimum is recommended.

- Minimal hard disk space needed.

2.7.3 CMES internal parameters

CMES uses several internal parameters to enable automated feature recognition, recetracking channel grouping and post processing. Table 1 lists the internal parameters in use.

Table 1 List of CMES internal parameters

Feature recognition	Minimum curvature radius, beyond which considered as fold
	Maximum angle between two element surfaces to be considered as sharp turn.
	Maximum acute angle between two connected element edges, which are considered from a straight line
	Maximum number of Racetracking channels we can deal with
	Minimal disturbance channel length to be considered.
Racetracking channels grouping	Minimal distance between parallel edges to be separated
Post processing	Maximum number of vents can be tolerated
	Minimum number of connected nodes that can be accounted as vent
	Minimum probability of a node being unfilled that should be taken out as potential vents

3 RESULTS AND DISCUSSION

CMES execution and validation was performed for several component geometries ranging from planar to complex 3-d curvatures. The following sections document three example problems:

- Sidewall of a vehicle shelter (planar 2-D)
- Blade stiffened curved laminate (3-D)
- Vehicle hood (3-D)

Exercises performed during META/iFAB integration activities in the program focused primarily on a chassis component provided by Vanderbilt. Results for this component are also provided.

3.1 Sidewall of Vehicle Shelter

The first example evaluated was a planar 2-D structure and is the sidewall of a vehicle shelter on the back of a tactical ground vehicle. The "indent" at the bottom represents the wheel well. CAD model for the example was generated in Pro-E and exported as a .bdf file to CMES. The following Figures show the execution sequence.

3.1.1 CAD model generation (Pro-E)

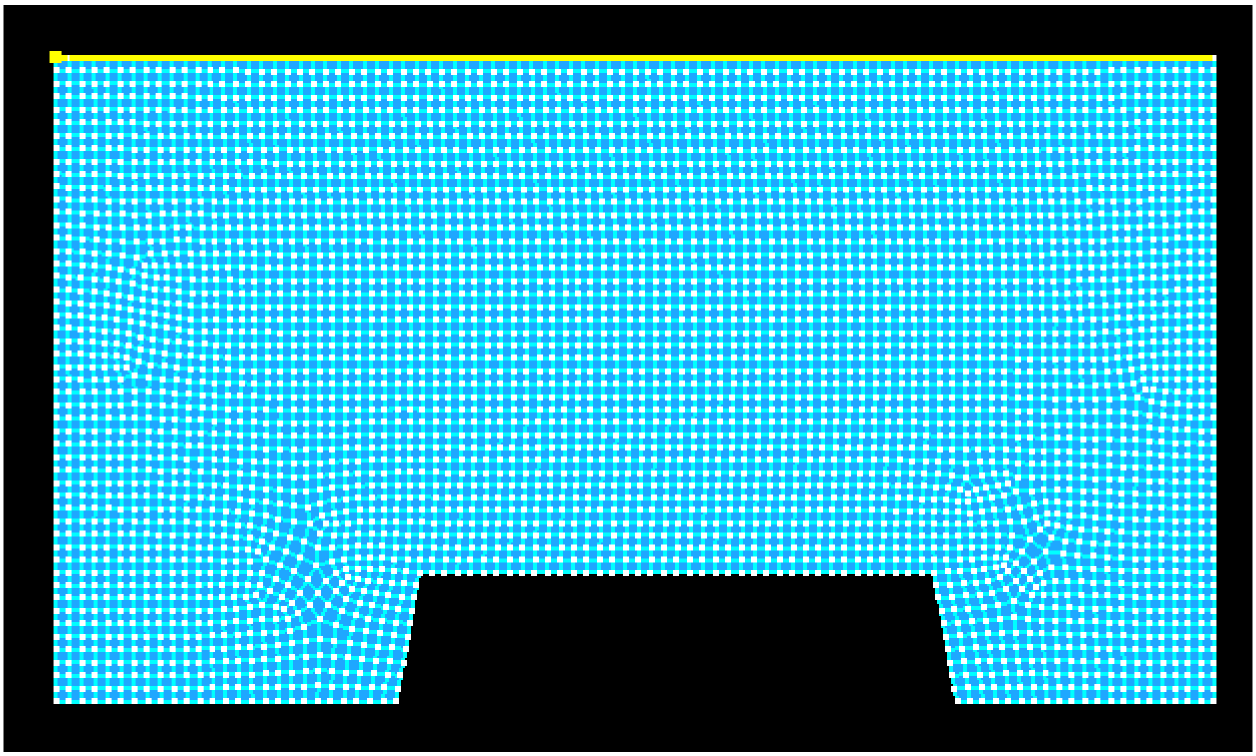


Figure 18 Simple sidewall plate CAD mesh

3.1.2 *Infusion Gate Options (Automated in CMS)*

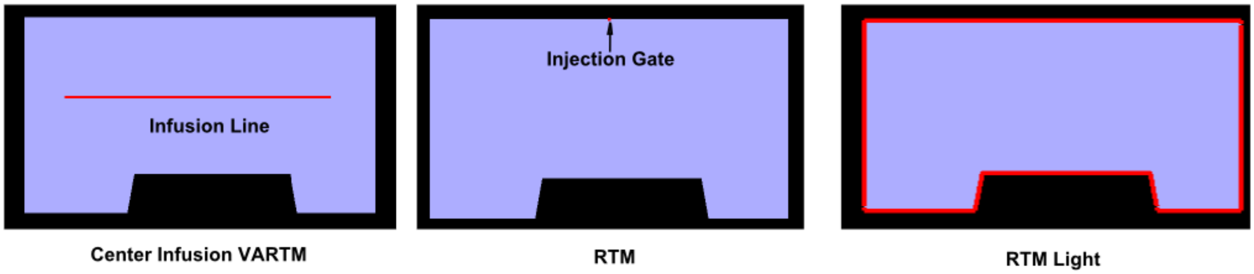


Figure 19 Infusion Plan

Three infusion plans have been run. First is VARTM with center infusion. Second is RTM, and then is RTM Light which sets outer boundaries as the resin infusion line.

3.1.3 *Racetracking prediction*

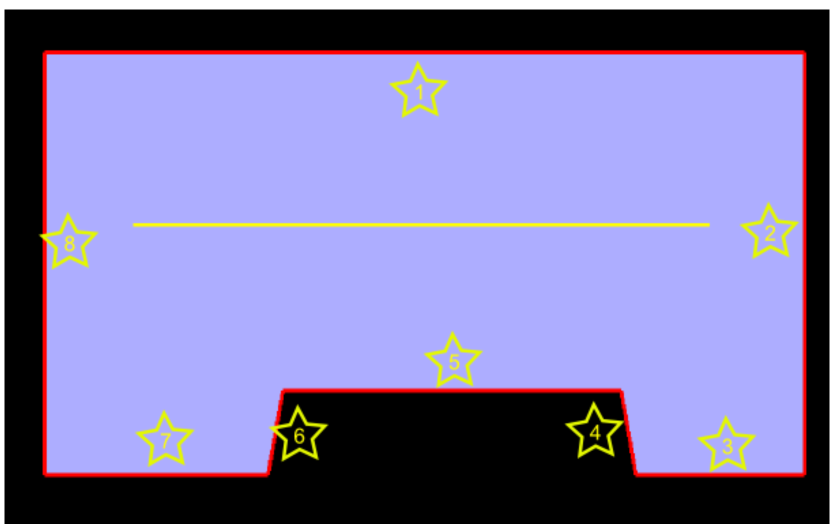


Figure 20 Racetracking prediction

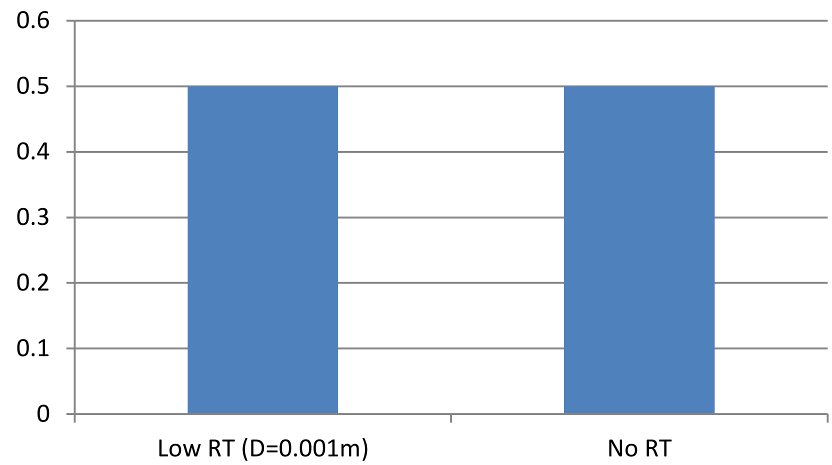


Figure 21 Racetracking probabilities assigned to the edges

Eight racetracking channels are detected as shown in Figure 19. Using a discretization of racetracking strength shown in Figure 20, 256 scenarios are expanded for VARTM and RTM. Since all the outer edges have been selected as infusion line in RTM light case, only one scenario is simulated.

3.1.4 Level 0 output

Table 2 Sidewall level 0 output

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

3.1.5 Level 1 output

Table 3 Sidewall level 1 output

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking	Process Scheme*	Flow Pattern*
VARTM	81.2092	3	NA	85	NA	NA
VARTM with Disturbances	334.755	2	NA	85	NA	NA
RTM Light	10.0792	1	NA	6	NA	NA
RTM Light With Disturbances	10.0792	1	NA	6	NA	NA
Center Infusion	182.237	2	NA	254	NA	NA
Center Infusion with Disturbances	1079.38	2	NA	254	NA	NA

Selected Process Scheme based on Cost Function:	RTM Light				
Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
What are the number of vents to completely fill part?	1	NA	NA	NA	Green

After calculating out the cost for VARTM, RTM and RTM light accordingly, RTM light is chosen for level 2 full simulation.

3.1.6 Level 2 output

Table 4 Sidewall level 2 output

Number of Vents	Yield
1	100%
Recommended Number of Vents	1

	Average	STDEV
Cycle Time	10.0792	0

Process Parameters	% of Failed Parts
Outer Edges	0
Folds	0
Bifurcations	0

Since the entire racetracking channels haven been selected as infusion line, RTM light lever 2 simulation only have to run one scenario. The resulted venting area is shown in Figure 21.

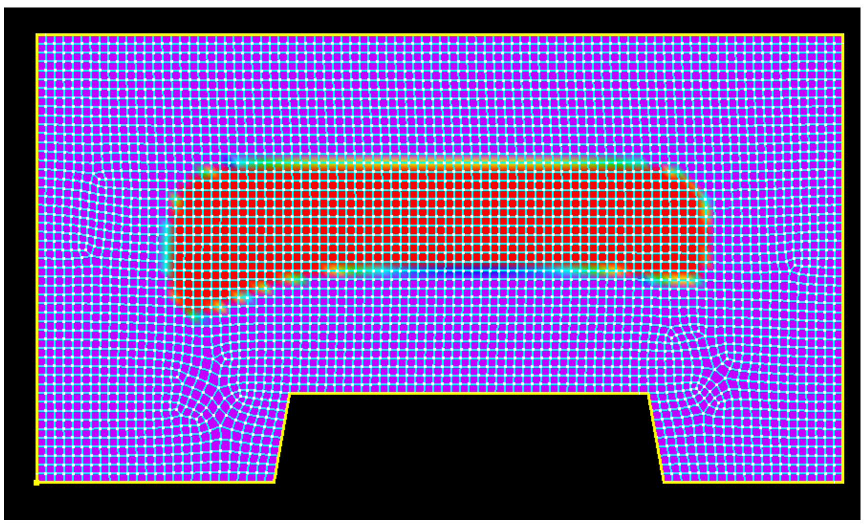


Figure 22 Vent plan for simple plate using RTM Light scheme

3.2 Blade stiffener

This component is a stiffened structure that is composed of a curved laminate (1-direction curvature) with blade stiffeners. Similar results flow is shown below.

3.2.1 *CAD model*

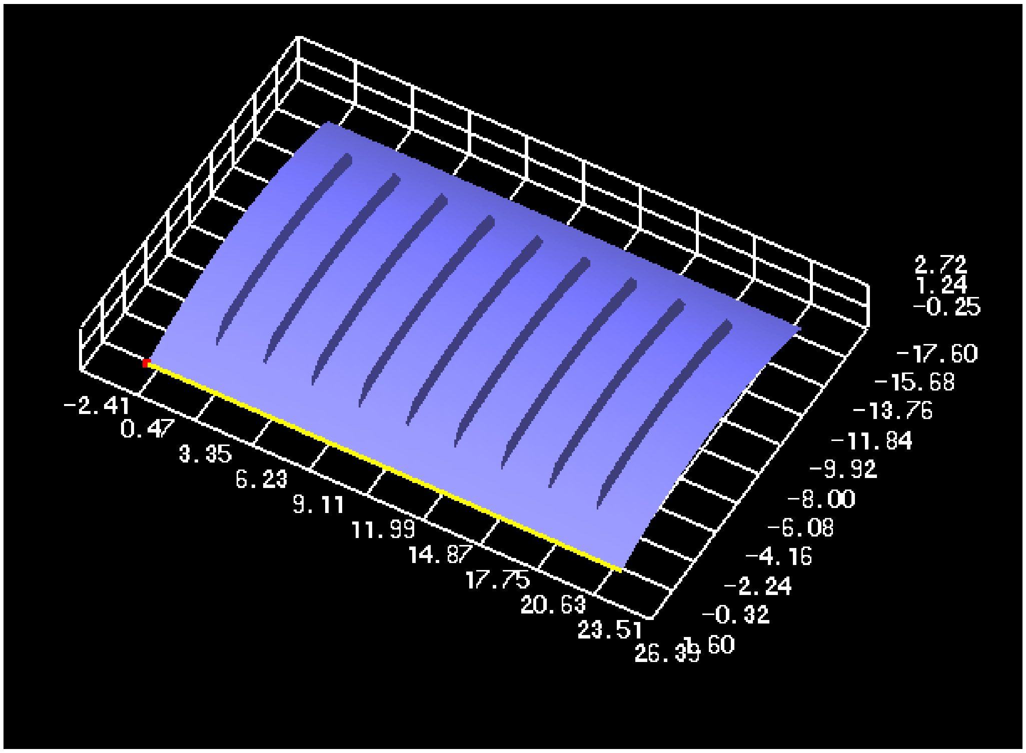


Figure 23 Stiffened blade CAD model (units in inches)

3.2.2 *Infusion plan*

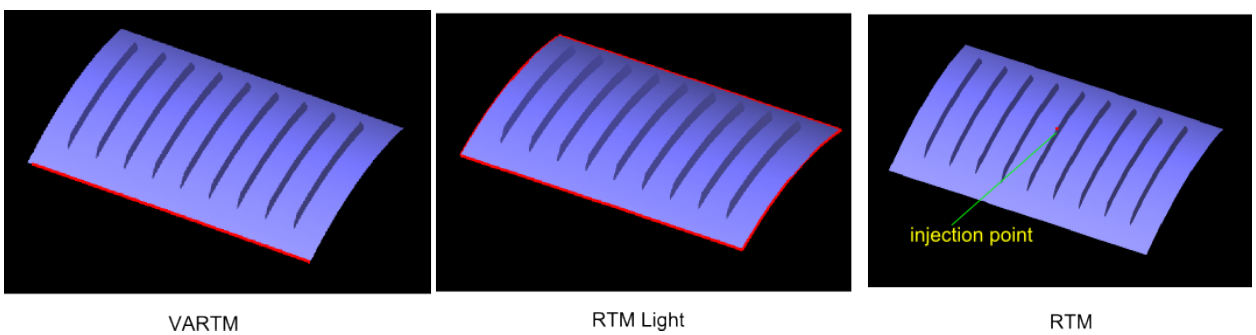


Figure 24 Infusion plan for the blade

3.2.3 Racetracking prediction

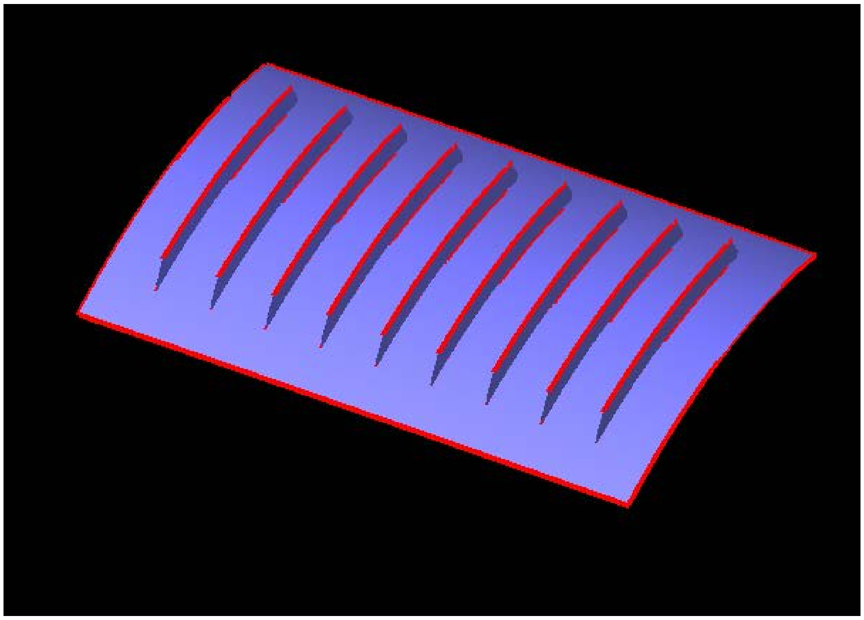


Figure 25 Racetracking prediction for the sitffened blade

3.2.4 Level 0 Output

Level 0 results in this case show a potential manufacturing problem – predicted fill time for the part exceeds the available resin pot life. This can be addressed through either selection of a different resin mix recipe (pot life varies based on the recipe), increase permeability by changing the selected fabric or changing the design so that the part can be fabricated in smaller sections.

Table 5 Stiffened blade level 0

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	No	Predicted fill time too high for resin pot life.	Choose a different mix recipe, make a smaller part, use a part with higher permeability.	NA	Red
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

3.2.5 Level 1

Table 6 Stiffened blade level 1 output

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking
VARTM	4811.08	1	NA	1273
VARTM with Disturbances	1547.07	0	NA	1273
RTM Light	1246.05	3	NA	438
RTM Light With Disturbances	933.661	3	NA	438
Center Infusion	18841.9	8	NA	4592
Center Infusion with Disturbances	4107.23	4	NA	4592

Selected Process Scheme based on Cost Function:	RTM Light				
Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
What are the number of vents to completely fill part?	3	NA	NA	NA	Green

3.2.6 Level 2

Table 7 Stiffened blade level 2 output

Number of Vents	Yield
1	0%
2	0%
3	100%
Recommended Number of Vents	3

	Average	STDEV
Cycle Time	1063.98	2795.09

Process Parameters	% of Failed Parts
Outer Edges	0
Folds	0
Bifurcations	0

3.3 Hood of a Tactical Vehicle

The final example problem is a realistic structure in use in ground vehicles – the hood of a tactical vehicle (HMMMWV or tactical trucks). This is a complex 3-D component with bi-directional curvature, as well as internal stiffeners. Similar flow is documented for this component.

3.3.1 CAD model

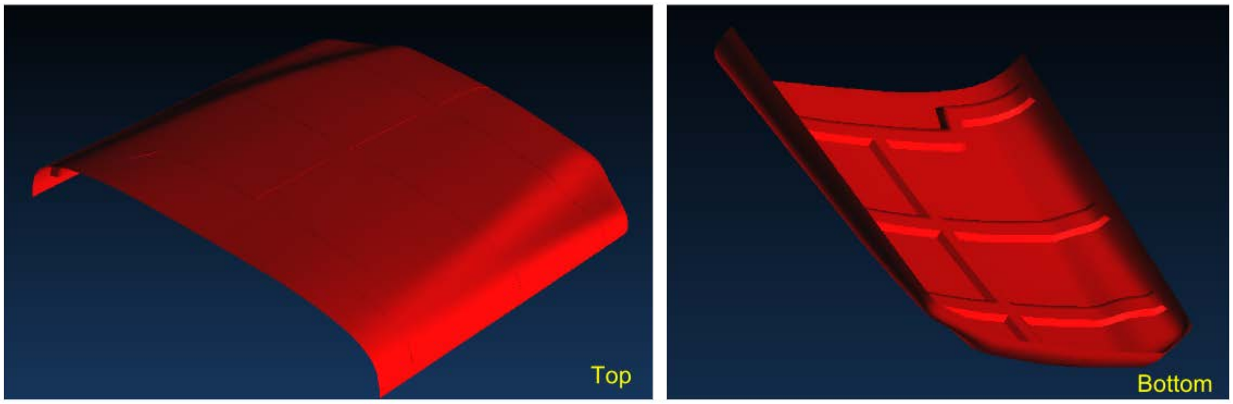
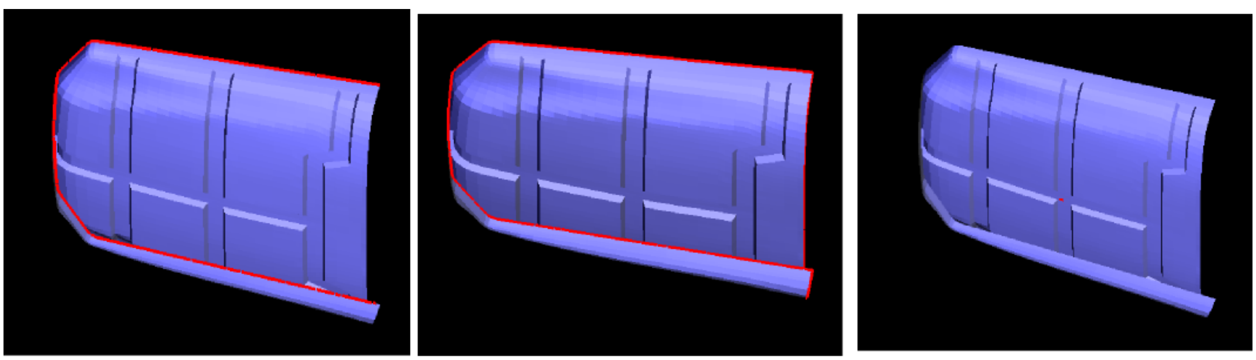


Figure 26 Top and bottom view of the hood

3.3.2 Infusion Plan



VARTM RTM Light RTM

Figure 27 Injection plans

3.3.3 *Racetracking prediction*

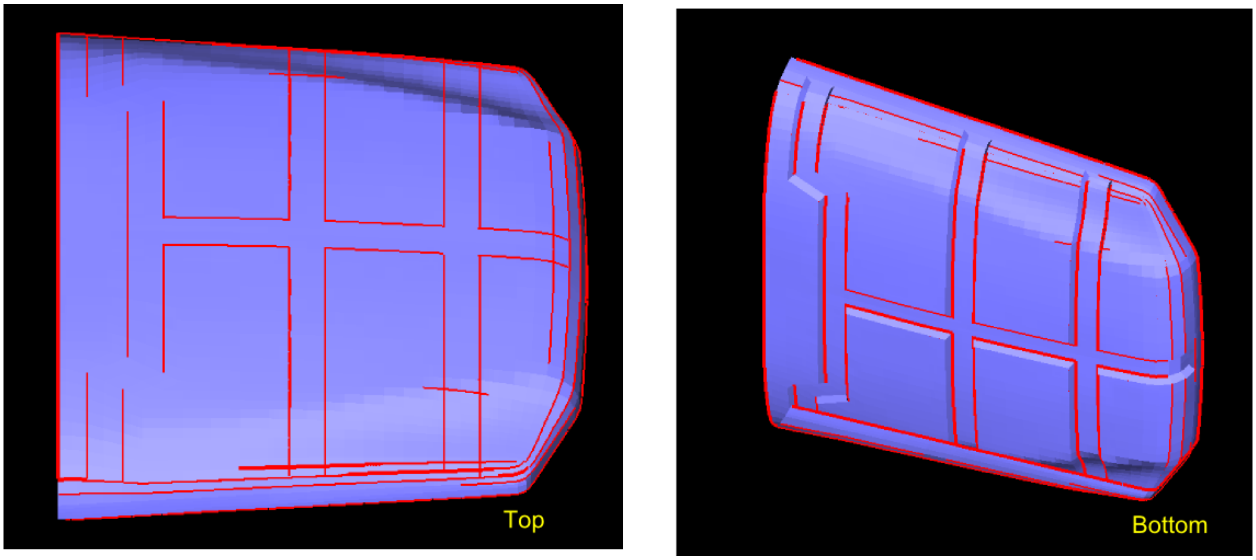


Figure 28 Racetracking channels prediction for the hood

3.3.4 *Level 0 Output*

Table 8 Hood level 0 check

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	No	Predicted fill time too high for resin pot life.	Choose a different mix recipe, make a smaller part, use a part with higher permeability.	NA	Red
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

3.3.5 *Level 1 Output*

Table 9 Hood level 1 output

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking
VARTM	16817.8	1	NA	5699
VARTM with Disturbances	11668.8	1	NA	5699
RTM Light	9805.89	1	NA	3452
RTM Light With Disturbances	7444.29	1	NA	3452
Center Infusion	93390.2	4	NA	34073
Center Infusion with Disturbances	76965	4	NA	34073

Selected Process Scheme based on Cost Function:	RTM Light				
Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	No	Resin pot life insufficient for part size	NA	Change resin to longer pot life system, or design in smaller components	Red
What are the number of vents to completely fill part?	1	NA	NA	NA	Green

Similar to the blade stiffened panel, this component also flags resin pot life as a concern. This is feedback that is provided to the designer, who must then make the design choice to address how this is to be addressed.

3.3.6 Level 2 Output

Table 10 Hood level 2 output

Number of Vents	Yield
1	100%
Recommended Number of Vents	1

	Average	STDEV
Cycle Time	8508.54	3869.95

Process Parameters	% of Failed Parts
Outer Edges	0
Folds	0
Bifurcations	0

3.4 iFAB-META Exercises

Exercises for iFAB-META integration were performed with a model assembly provided by Vanderbilt (META performer). The Figure below shows the example assembly, which consisted of a number of components. The largest component of the assembly (chassis) was extracted for CMES evaluation as part of the exercise.

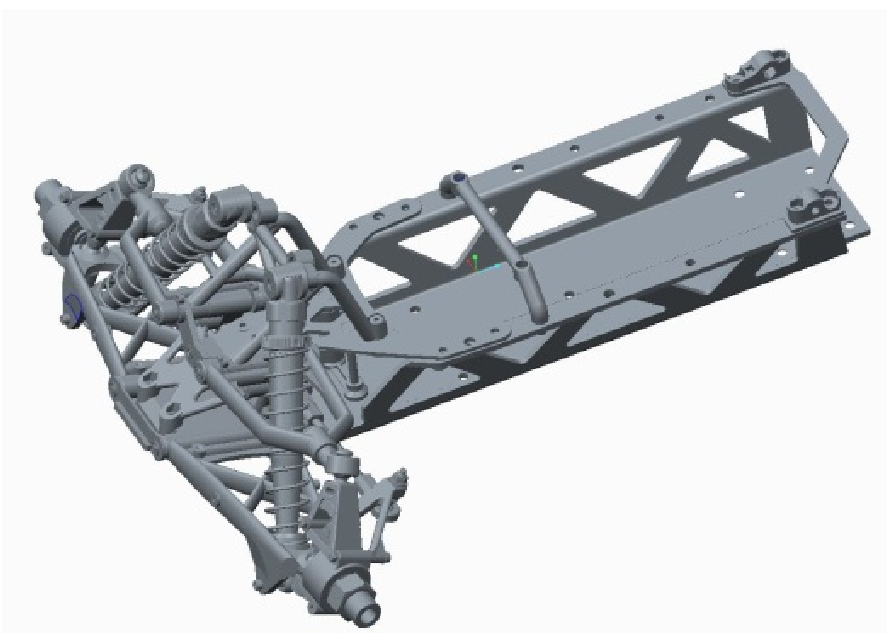


Figure 29 Component Assembly provided as part of iFAB-META Exercise

Our approach to this assembly was to look at the largest component as a validation exercise for CMES. All the other components are too small for liquid molding or are off the shelf

COTS items and not considered in this exercise. Additionally, the extracted chassis was modified by removing all “machined” features from the component, as shown below. Our assumption is that the final component geometry (shown to left) can be easily achieved through machining a composite “blank” which would be manufactured through liquid molding.

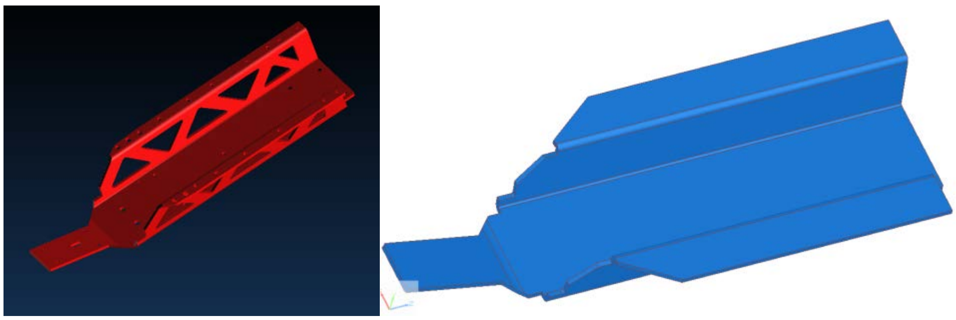


Figure 30 Extracted chassis component (left) and composite blank (right)

An example process flow from the assembly is shown below. PARC (another iFAB performer) could perform assembly decomposition and extract the chassis, send a request for composite blank manufacturability assessment to CMES, which would return that information back to PARC. The META user would receive this information through PARC’s code and create design changes as needed. Following a successful CMES run, manufacturing parameters would be identified for the blank and PARC’s code notified of the successful run. PARC would then perform virtual machining operations and provide manufacturability assessment of those operations back to the META user, before combining the finished chassis component back into its assembly.

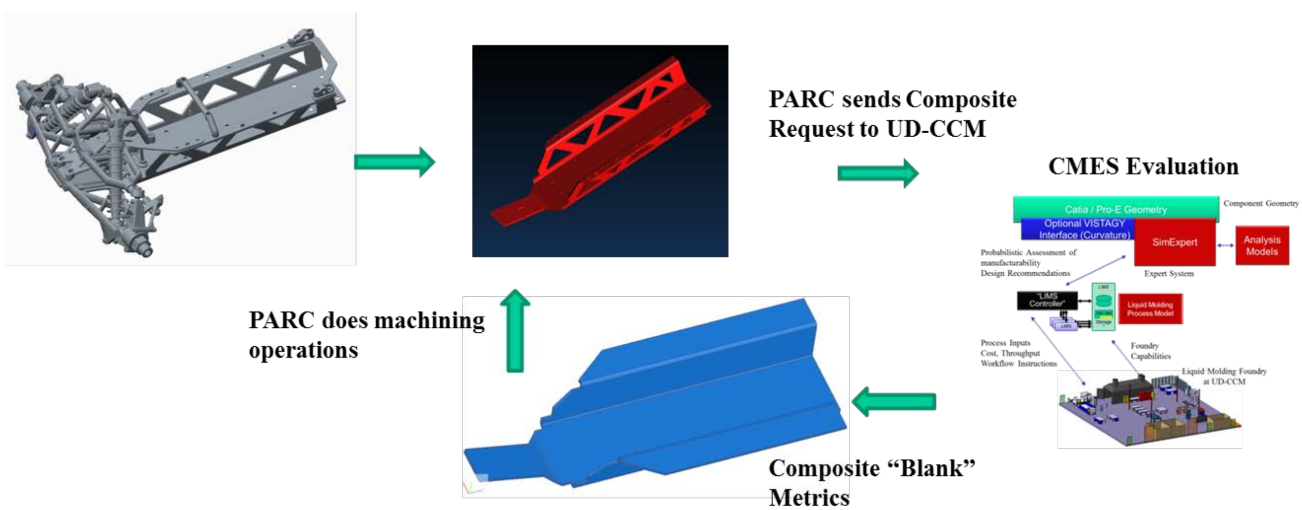
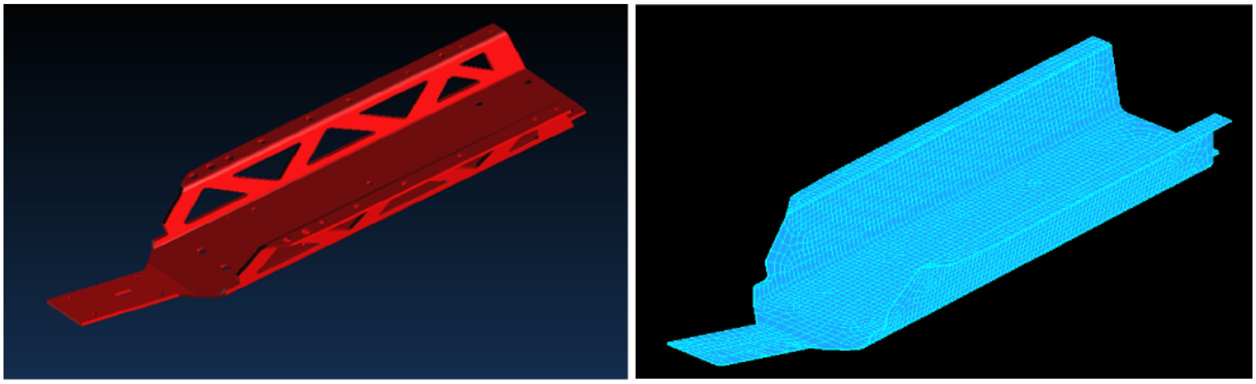


Figure 31 Example iFAB collaborative program flow. PARC’s code generated CMES evaluation request for a composite component, with post-machining evaluation performed by their code.

CMES program flow and output is shown below.

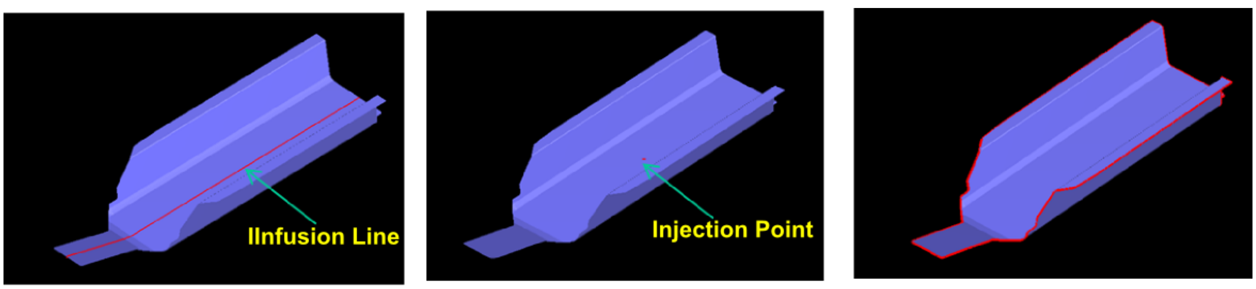
3.4.1 CAD Model



(a) CAD model of the Chassis (b) Mesh with holes compressed

Figure 32 CAD model and Mesh

3.4.2 Injection plan initiation



(a) VARTM **(b) RTM** **RTM Light**

Figure 33 Three infusion plans

3.4.3 Racetracking forecast

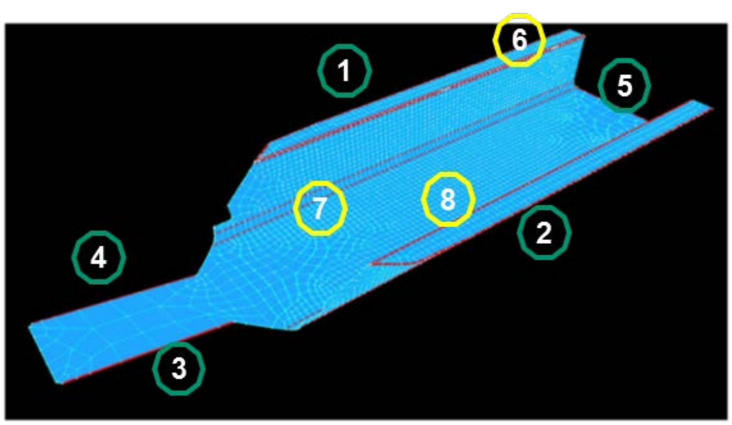


Figure 34 Eight potential Racetracking channels

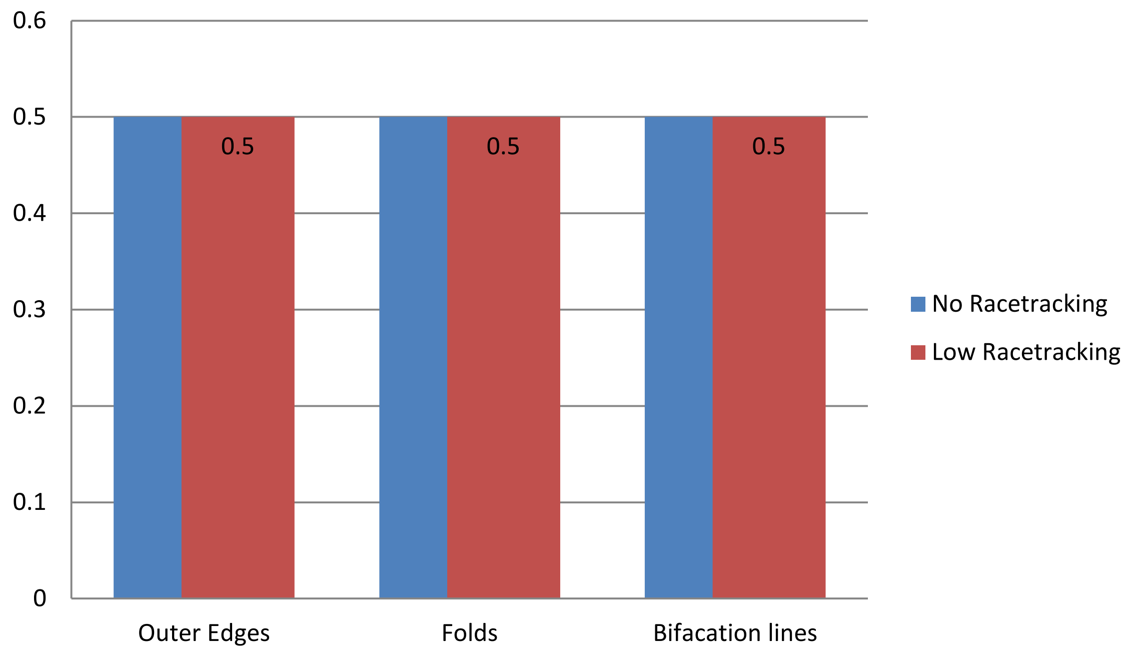


Figure 35 Racetracking strength probability discretion

3.4.4 Assumptions for model parameters in CMES

Section 3.7.3 documented a list of CMES internal parameters that are used for various geometries. Values of the parameters for the chassis component are documented below.

Table 11 Assumptions for the chassis

Feature recognition	Minimum curvature radius, beyond which considered as fold	0.049m
	Maximum angle between two element surfaces to be considered as sharp turn.	105(deg)
	Maximum acute angle between two connected element edges, which are considered from a straight line	20(deg)
	Maximum number of Racetracking channels we can deal with	10
	Minimal disturbance channel length to be considered.	0.024m
Racetracking channels grouping	Minimal distance between parallel edges to be separated	0.066m
Post processing	Maximum number of vents can be tolerated	5
	Minimum number of connected nodes that can be accounted as vent	5

Minimum probability of a node being unfilled that should be taken out as potential vents	10%

3.4.5 Level 0 check

Table 12 Chassis Level 0 output

Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
Can the foundry handle selected reinforcement?	Yes	NA	NA	NA	Green
Is reinforcement in fabric form amenable to infusion processes?	Yes	NA	NA	NA	Green
Can the foundry process the selected resin/polymer?	Yes	NA	NA	NA	Green
Are reinforcement and resin compatible	Yes	NA	NA	NA	Green
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
If structure has core, can core handle resin cure or post-cure temperature?	Yes	NA	NA	NA	Green
Are dimensions within foundry limits?	Yes	NA	NA	NA	Green
Can foundry handle part weight?	Yes	NA	NA	NA	Green
Is the fiber volume fraction possible with foundry processes?	Yes	NA	NA	NA	Green

3.4.6 Level 1 output

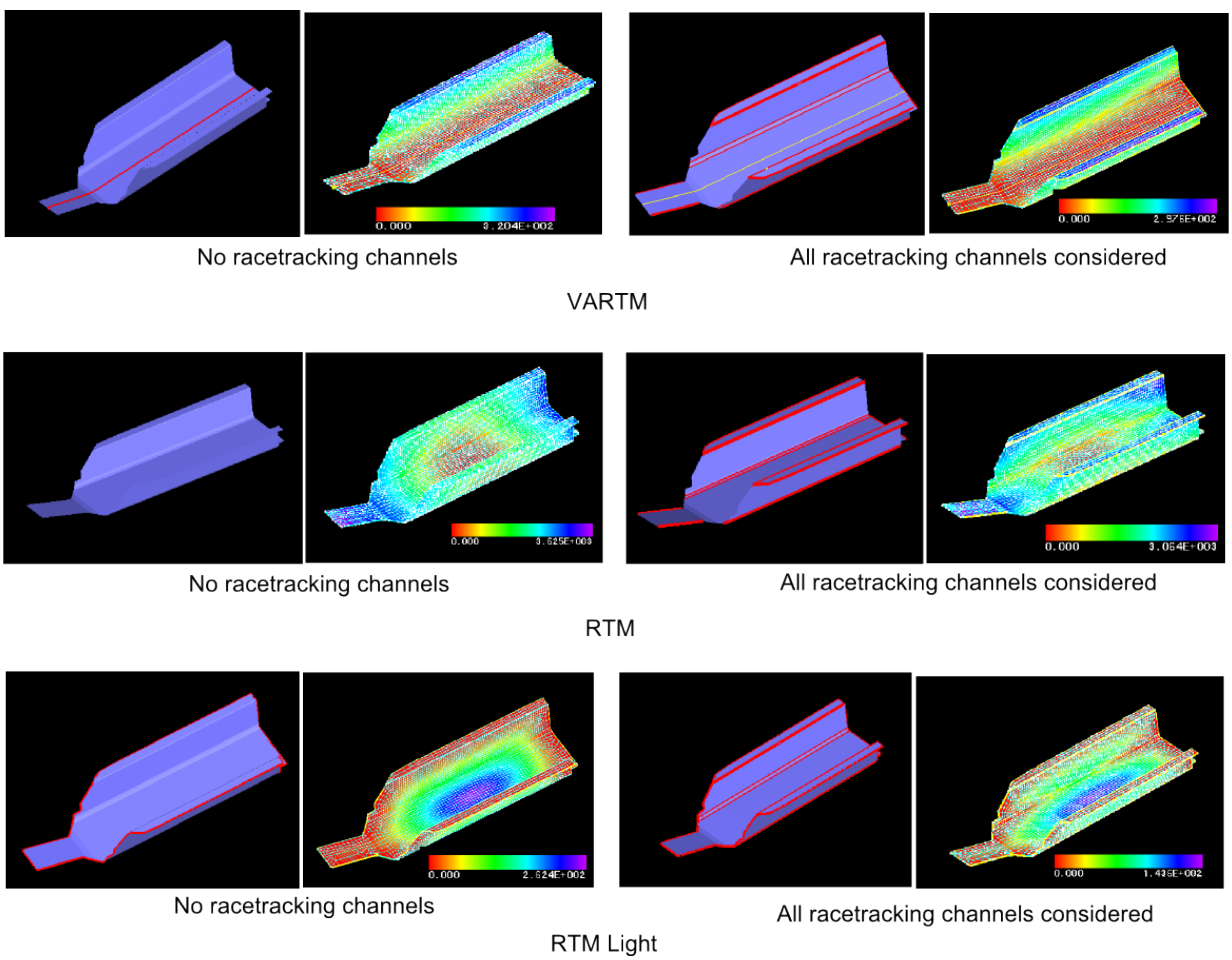


Figure 36 Level 1 scenarios for chassis

Table 13 Chassis Level 1 output

Process Scheme	Cycle Time	Number of Vents	Cost	Cost Function Ranking	Process Scheme*	Flow Pattern*
VARTM	320.414	2	NA	119	NA	NA
VARTM with Disturbances	264.1	2	NA	119	NA	NA
RTM Light	262.421	1	NA	83	NA	NA
RTM Light With Disturbances	145.56	1	NA	83	NA	NA
Center Infusion	3625.11	2	NA	1313	NA	NA
Center Infusion with Disturbances	2931.33	4	NA	1313	NA	NA

Selected Process Scheme based on Cost Function:	RTM Light				
Query	Response	Reason If No	Design Recommendations	Process Recommendations	Status
If dry fabric and resin specified, is resin pot life sufficient to fill the part?	Yes	NA	NA	NA	Green
What are the number of vents to completely fill part?	1	NA	NA	NA	Green

3.4.7 Level 2 output

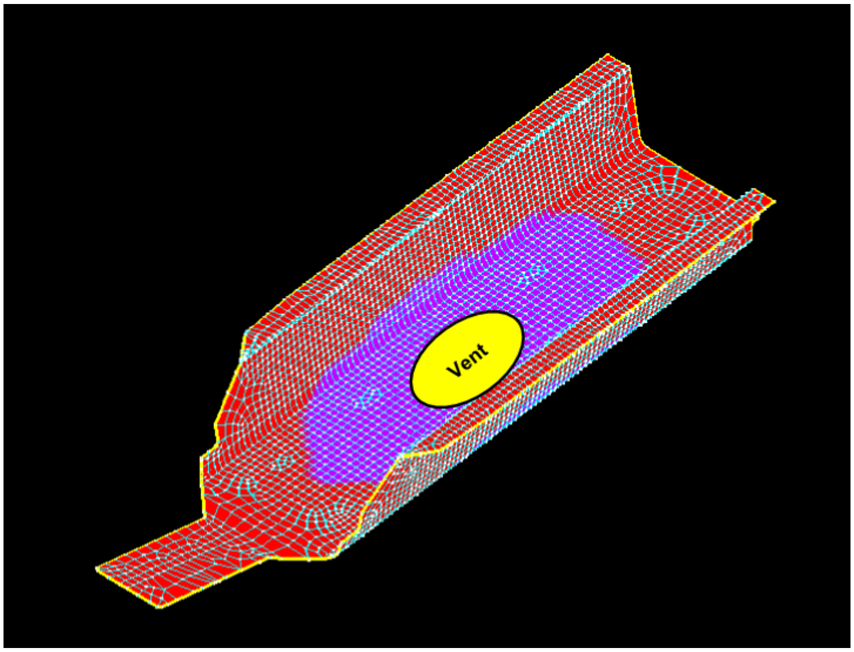


Figure 37 Vent plan for the selected process scheme (RTM Light)

Table 14 Chassis Level 2 output

Number of Vents	Yield
1	100%
Recommended Number of Vents	1

	Average	STDEV
Cycle Time	200.288	38.9921

Process Parameters	% of Failed Parts
Outer Edges	0
Folds	0
Bifurcations	0

3.4.8 CCM/PARC Integration Exercise

An integration exercise was carried out between CCM and PARC to demonstrate the

process flow shown in Figure 31. The extracted solid model (Original Solid) was converted to a composite blank (Composite Model) followed by CMES evaluations, the results of which were documented in the previous sections. Following completion of CMES runs, the blank geometry was provided to PARC (in CAD format) for post-machining operations to create the chassis model, as shown below. The Decomposed Negative Solid shows the material removed from the composite blank during machining operations to generate the original desired geometry.

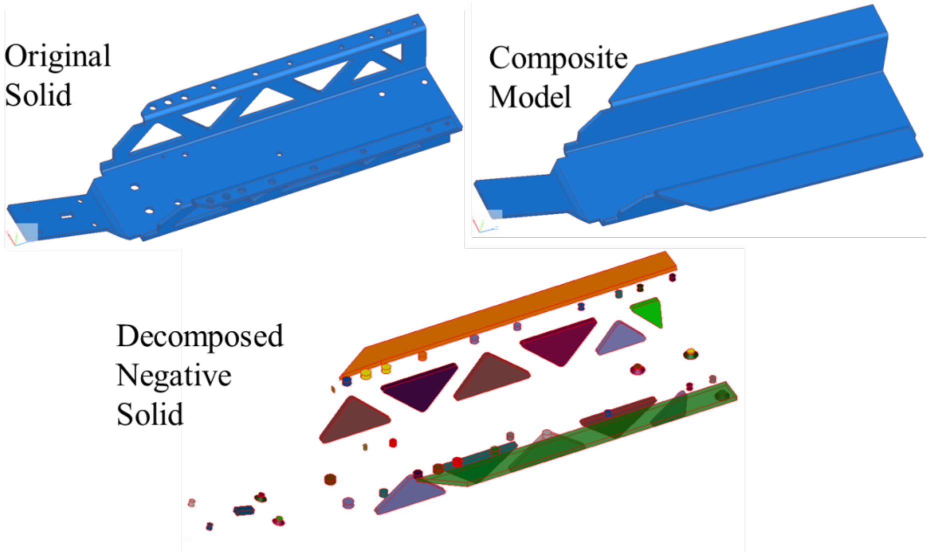


Figure 38 Integration exercise on chassis with PARC

3.5 Cost data for CMES

In this effort, cost modeling was performed at a simplistic level to generate estimated costs for components that could be evaluated with CMES. A series of composite panels which capture common variables in composite part design and the Liquid Molding process were fabricated and actual costs captured during the fabrication process. Several variables were investigated: basic geometry, number of plies, fabric material (carbon vs. glass), cored construction, co-molded stiffeners, curved vs. flat panels, semi-permeable membrane infusion aid. Table 15 documents the various composite components that were fabricated to generate cost estimates for UD-CCM's liquid molding foundry. These results were used to provide simple ROM estimates for cost in CMES.

Data generated in Table 15 can be used to generate simple feature-based equations for cost predictions, if so desired. Detailed cost assessments were not performed as this depends significantly on specific foundry lay-outs, workcells and process planning. It is expected that cost models of the foundries in question will be generated by the Foundry Performer and the network selected distributed manufacturing sites as part of the iFAB Foundry.

Table 15 Components fabricated at CCM facility to generate cost data for CMES

ID	Surface Area	Material	Thickness	Foam Core (1.0" thick)	Net shape	Co-molded Stiffeners	Curved Tooling	Seams	Membrane	Co-molded Inserts	Cost
001-001	36" x 36"	S2 Glass	~0.2"								$402.93
001-002	36" x 36"	S2 Glass	~0.2"								$338.43
001-003	36" x 72"	S2 Glass	~0.2"								$652.17
001-004	36" x 72"	S2 Glass	~0.2"					X			$558.73
001-005	36" x 36"	S2 Glass	~0.2"		X						$623.39
001-006	36" x 36"	Carbon	~0.2"								$378.45
001-007	36" x 36"	S2 Glass	~0.2"		X				X		$681.58
001-008	36" x 36"	S2 Glass	~0.2"		X						$601.56
001-009	36" x 72"	S2 Glass	~0.2"							X	$719.29
002-001	36" x 36"	S2 Glass	~0.5"								$488.70
003-001	36" x 36"	S2 Glass	~1.2"	X					X		$343.37
003-002	36" x 72"	S2 Glass	~1.2"	X					X		$719.87
004-001	36" x 72"	S2 Glass	~0.2"				X				$719.87
005-001	36" x 72"	S2 Glass	~0.2"			X					$1,159.56
005-002	36" x 72"	S2 Glass	~0.2"			X	X				$1,314.95
005-003	36" x 72"	S2 Glass	~0.2"			X (transverse)	X				$1,197.86

3.6 Summary

A Composites Manufacturability Evaluation System (CMES), a software tool that provides manufacturability assessments for composite components for the Liquid Composite Molding class of processes, has been developed in this effort. The core of CMES is a physics-based process modeling tool called LIMS (Liquid Injection Molding Software) that predicts resin flow and filling of complex 3-D geometries with a selected reinforcement or fabric. Process variability is quantified using a probabilistic approach to look at variations in material properties, process parameters and process disturbances. Manufacturability assessments are done at three (3) levels of abstraction ranging from feasibility assessments (Level 0), process variant assessment (Level 1) and probabilistic assessment of the selected Level 1 process. CMES performs these analyses within the scope of a specific foundry configuration, hence the capabilities of the composites foundry that is being considered for component fabrication need to be documented. Modifications to the component design can be performed based on these recommendations and resubmitted for CMES analyses.

For each level of abstraction, CMES provides assessments and design/process recommendations to the user. Level 0 evaluates process feasibility and only requires material data, component bounding box and foundry capability. Level 1 provides part cycle times,

infusion schemes and a recommended process selection back to the user, in addition to manufacturability assessment. Level 2 provides a probabilistic evaluation of the recommended Level 1 process scheme with yield vs process scheme, cycle time variability and a summary of dominant parameters that affect variability. CMES validations have been performed for a variety of components ranging from simple geometries (flat laminates) to complex doubly curved geometries (composite vehicle hood with stiffeners).

4 CONCLUSIONS

There are a number of manufacturing processes available to fabricate structure and armor components for vehicle platforms. Due to the general range of component sizes, materials and requirements, Liquid Molding processes have emerged as the ideal class of manufacturing process for vehicle structures as well as composite armor. The UD-CCM iFAB effort focused on this particular class of composite manufacturing processes and created automated tools for manufacturability assessment of composite components, called Composite Manufacturability Evaluation System (CMES). The core of CMES is a physics-based process modeling tool called LIMS (Liquid Injection Molding Software) that predicts resin flow and filling of complex 3-D geometries with a selected reinforcement or fabric.

Manufacturability assessments are done at three (3) levels of abstraction ranging from feasibility assessments (Level 0), process variant assessment (Level 1) and probabilistic assessment of the selected Level 1 process. The first two levels of design feedback are tailored to help the designer decide whether this is a workable manufacturing process for this particular design, whereas final design feedback will focus more on quantifying process uncertainty. Feedback for conceptual design considers the component geometric envelope, materials (fiber/fabric and resin) and the capability of the foundry in which the component is to be fabricated. Based on this low fidelity analysis we return a simple yes/no on manufacturability and a preliminary cost and time estimate based on experiential averages (range of $/lb or $/sq ft). Design or process modifications are suggested based on the specific manufacturability criteria. Note that CMES manufacturability queries are hard coded, as it is not feasible to expect a META user to be a composites expert and ask the necessary and sufficient set of questions for a complete manufacturability assessment.

Feedback for intermediate and final designs (Levels 1 and 2) will require a meshed CAD model of the component. Automated meshing is available in all CAD software tools. At this stage of design, a “ply book” should be completed, which documents the number of fabric layers, orientation of each layer, thickness, ply sequencing nomenclature, point of origin (for reference) and principle material directions. Other material properties include fabric permeability, assumed fiber volume fraction, resin properties including viscosity and cure cycle, core (if sandwich structure) and any inserts and its attributes (such as for joint locations). A Foundry Specification file provides foundry constraints for the process simulation and an option is available for the user to specify a starting process plan. If no plan is provided, automated generation of process plans will occur. A number of process variants are evaluated for the component and manufacturing metrics returned to the user. These include manufacturability assessment for each process variant (yes/no), optimal parameters for each, and recommendations on the optimal process plan for Level 2 analysis.

Level 2 analysis addresses process uncertainty quantification for the optimal Level 1 (intermediate design stage) process plan selected. Due to the number of runs needed to realize high fidelity results, we do not anticipate real-time design feedback for this case. The Foundry Specification file documents the variability in process parameters at the Foundry, human factors that impact the process, and any other parameters that impact uncertainty in the manufacturing process. For the selected process plan, a probabilistic assessment quantifies and predicts expected part yield, and variability in manufacturing metrics (cycle time, dimensions, volume fractions etc.). Completion of this step generates the final build to print for the component, which

can be provided to the Composite Node for setup and instruction generation.

Validation exercises for CMES have been performed for components with increasing complexity and results showing manufacturability assessments from Level 0 through to Level 2 have been documented. These range from simple flat 2-D geometries to double curved stiffened 3-D geometries. Attempts have been made to reduce run times for Level 2 assessments; however probabilistic assessments by their very nature require significant number of code executions to generate statistical results.

5 REFERENCES

1. Simacek, P. and Advani, S.G., "Desirable Features in Mold Filling Simulations for Liquid Molding Processes," Polymer Composites, 25, 2004, p 355-367

2. Bruschke, M. and Advani, S.G., "Finite Element/Control Volume Approach to Mold Filling in Anisotropic Porous Media," Polymer Composites, 11, 1990, p 398-405.